

Weld Shrinkage Study

U. S. DEPARTMENT OF THE NAVY
CARDEROCK DIVISION, NAVAL SURFACE
WARFARE CENTER

in cooperation with

Newport News Shipbuilding

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**THE NATIONAL SHIPBUILDING
RESEARCH PROGRAM**

WELD SHRINKAGE STUDY

SUBMITTED TO:

**SHIP PRODUCTION COMMITTEE
DESIGN/PRODUCTION INTEGRATION PANEL**

BY

**NATIONAL STEEL AND SHIPBUILDING COMPANY
HARBOR DRIVE AND 28TH STREET
SAN DIEGO, CALIFORNIA**

FOREWORD

The National Shipbuilding Research Program (NSRP) is a cooperative effort of the U.S. Navy and the United States shipbuilding industry. This report is the product of NSRP performed for the Design/Production Integration Panel (SP-4) of whom W.G. Becker is the program manager.

This study will benefit the shipbuilding industry serving as a reference guide for shipyard engineers in the development of weld shrinkage factors. Shrinkage data collection methodology and statistical analysis is provided with the shrinkage factors derived, for each stage of fabrication.

The project was performed by R. E. Doersksen, Assistant Welding Engineer, and directed by David L. Malmquist, Production Engineer, of the Steel Planning Department. Appreciation is expressed to Ken Coblenz, Staff Engineer, for initiation of the project and establishing Shrinkage Collection Procedures, and also to those who assisted with laboratory experiments and data collection, especially A. D. Hunter, L. C. Swoboda, and A. A. Ramirez.

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ABSTRACT:

Inherent in the ship hull construction during assembly of interim products is weld shrinkage. Shipbuilders have recognized this fact and they realize the necessity of planning added material into the design phase to compensate for weld shrinkage. The traditional method to compensate for shrinkage has been to add excess material, usually 1" of material on two sides of a block, that would be trimmed at the erection stage. Normally, this 1" of material would be adequate to compensate for any weld shrinkage incurred during block assembly. It is however, a commitment to rework.

Modern shipbuilders, employing New Construction Building Techniques, are attempting to eliminate this commitment to rework. By adding just enough material to compensate for weld shrinkage at each of the interim processes, a "neat" hull block can be built. In order to accomplish this task, extensive data gathering of shrinkage at each interim process must be conducted. Results of the data gathering will then be analyzed and shrinkage factors for each of the interim processes will be developed. These shrinkage factors will then be communicated to the Hull Engineering Department for inclusion into the detailed hull block design.

Shrinkage factors for interim processes may vary from shipyard to shipyard due to facilities, welding equipment, joint design, welding sequence, ambient temperature, and type of material. Establishing and maintaining shrinkage factors is an investment shipyards make in improving productivity.

Through this study, the process of deriving shrinkage factors will be identified; from the development of check sheets, to establishing checking procedures, data gathering, and the statistical analysis of data. Remembering that a variety of variables can effect the determination of a shrinkage factor, emphasis will be placed on the "How to" of the process.

1.0 INTRODUCTION

The process of determining shrinkage factors for three different stages of construction is the task of this study. This can be accomplished by an extensive collection of shrinkage data. The different stages of block assembly and erection are referred to as interim processes. The three selected processes are plate panel butt shrinkage, hull block assembly shrinkage, and butt erection joint shrinkage. Through this study, the process and methods for gathering shrinkage data were determined for each of the interim processes.

Data collection sheets were specially formatted with all the necessary attributes and independent variables that affect joint shrinkage. Shrinkage data was collected and organized in data sets by the welding process and application. Included in each section is the statistical analysis of data and shrinkage factors derived.

1.1 INTERIM PROCESSES:

In the first interim process, shrinkage data was collected from panel butt joints. Weld shrinkage in the direction transverse to the butt joint was analyzed. The second interim process, is the assembly stage, which consists of both longitudinal and transverse panel shrinkage data from stiffened panels. In this construction stage fillet weld joint shrinkage data was analyzed. The third interim process, erection butt joint shrinkage data was collected for the various welding positions. Flow charts for each interim process page 6, 32, and 41 respectively illustrate the breakdown of each interim process by the attributes of the welding environment.

Dimensional loss also results from weld shrinkage which causes angular distortion and panel buckling. The magnitude of these two types of distortion is limited with the implementation and control of welding procedures.

1.2 DATA COLLECTION METHODOLOGY:

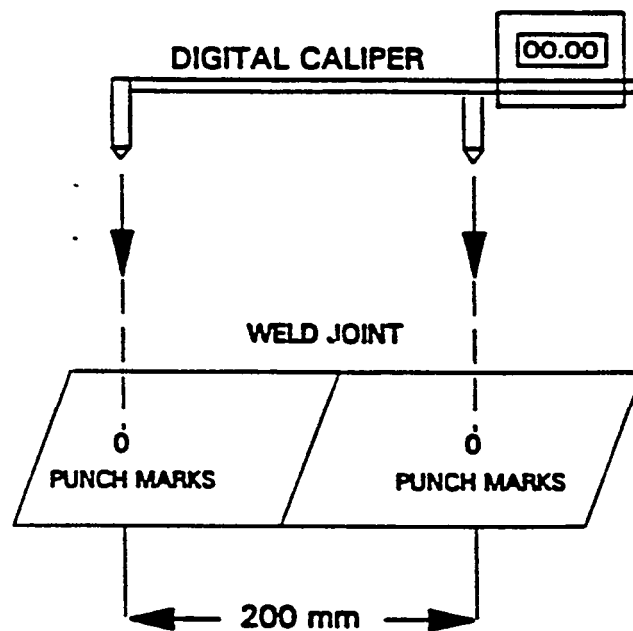
Collection of shrinkage data for the transverse butt joints required a measurement technique which would remain consistent throughout the project. The reliability provided by a 200 mm digital caliper, as well as the ease in reading its display, made it a logical choice for determining shrinkage dimensions. As permanent data points were established using a steel punch, repetitive checks were conducted, which ensured a tolerance of $\pm .05$ mm.

Data collection of hull block assembly shrinkage for the fillet weld joint design was accomplished with a tape measure in directions both longitudinal and transverse to the direction of the welded stiffeners.

Data sheets were developed for the attributes that affect weld shrinkage. A sample of the data sheets used in this study are displayed at the end of each section for each interim process (pages 29,39, and 84 respectively).

1.3 **MEASUREMENT TECHNIQUES:**

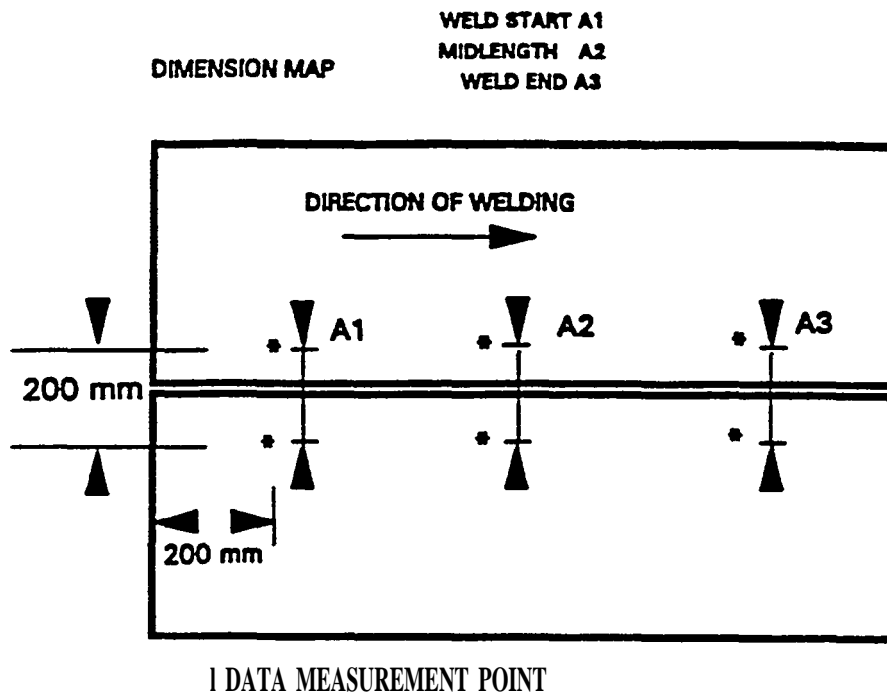
- 1.3.1 Butt Joint Shrinkage - Shrinkage data gathered for both the first and third interim process was from a butt joint weld design. Pre-weld joint measurements were taken with a 200 mm caliper, in two punched marks, across the fitted joint (Figure 1-1).



General Measurement Diagram for Butt Joint
- Figure 1-1.

At each weld joint, three (3) measurement locations were recorded. These locations were labeled A1, A2, and A3 for identification purposes, and also for identifying the direction of weld progression at the weld start, mid-length, and weld end locations respectively (Figure 1-2).

BUTT JOINTS



LOCATIONS FOR TRANSVERSE SHRINKAGE MEASUREMENTS

- Figure 1-2-

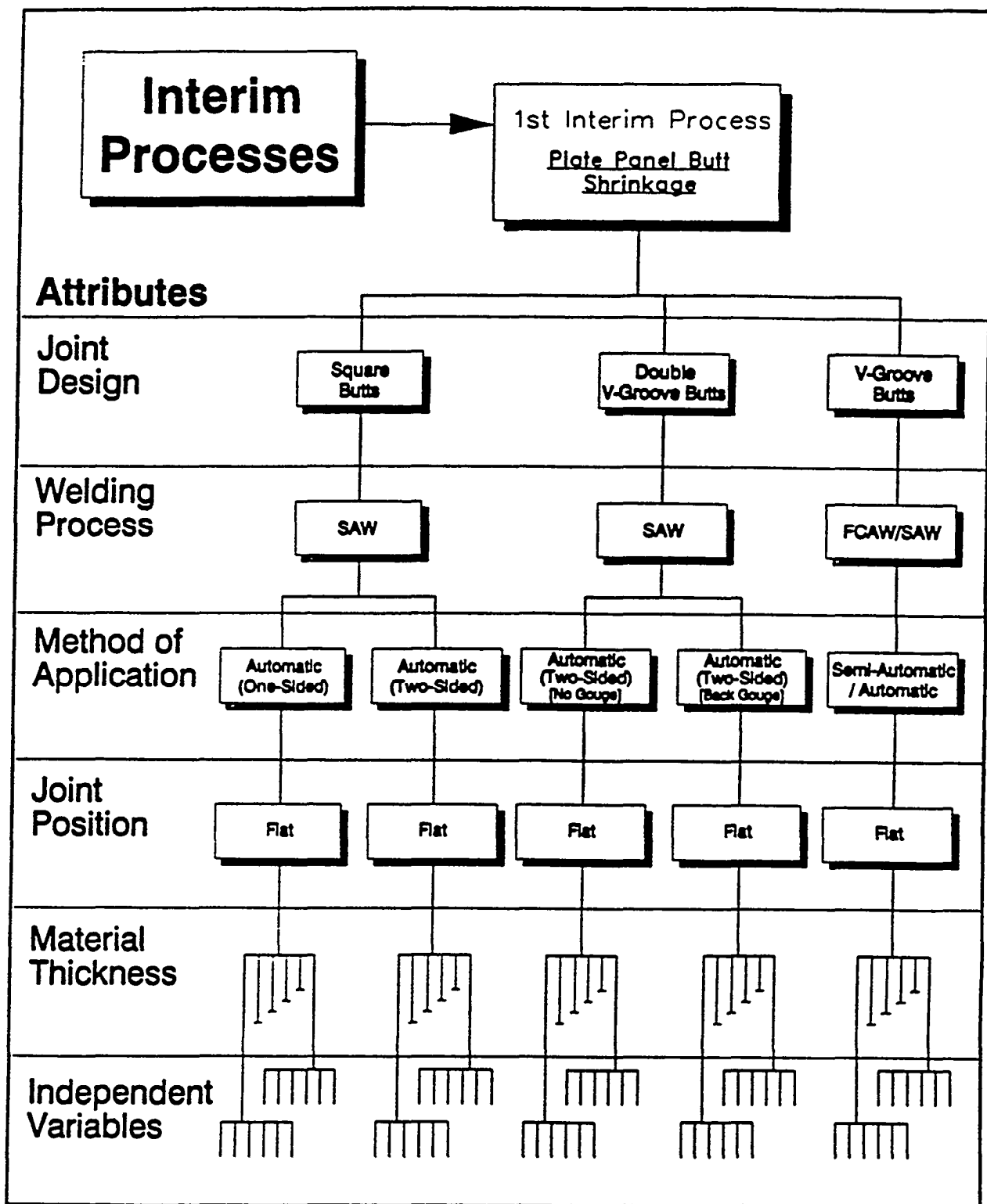
- 1.3.2 Assembly Shrinkage- Transverse shrinkage measurements were taken with a tape measure placed through the stiffener rat holes adjacent to the panel edge. These measurements were recorded along with the number of stiffeners, the material weight and independent variables.

Shrinkage measurements parallel to the stiffener direction were taken at the outboard edge and recorded together with the distance from the closest positioned stiffener. Panel shrinkage in this direction is a result of longitudinal weld-metal contraction.

1.4 WELDING ATTRIBUTES:

Shrinkage data from each interim process was grouped by the following six welding attributes. Knowledge of each of these attributes is important to understanding the mechanisms that cause weld shrinkage. Changing any one of these attributes, would change the characteristics indicative of the process that affect weld shrinkage. As illustrated in the flow chart (Figure 1-3) for the first interim process, three joint designs, although all butt joints, are divided into three categories because each affects the mechanisms that cause weld shrinkage differently. The next attribute describes the method of application or technique the welding process is utilized. The final factor in distinguishing a weld shrinkage data set is the position of the joint. When the position of the joint changes, so do the welding heat input requirements. Of the welding attributes that are included in a shrinkage data set, the only changing attributes are material thickness and the independent variables. The range of material thickness is established for each data set, and all shrinkage data is organized according to the material thickness of the joint.

- Ž Joint Design**
- Ž Welding Process**
- Ž Method of Application**
- Ž Joint Position**
- Ž Material Thickness**
- Ž Independent Variables**



- Figure 1-3 -

- 1.4.1 **Joint Design** - Two (2) groups of joint designs were evaluated in this study. Shrinkage data is organized by these joint designs, butts and fillets. There are types of butt joint designs, two (2) of these are included in this evaluation, square butt and V-groove joints.
- 1.4.2 **Welding Process** - Three (3) welding processes, SMAW (Shielded Metal Arc Welding), FCAW (Flux-Cored Arc Welding), and SAW (Submerged Arc Welding) are the most common in ship hull production. There are applications in which two (2) are used in combination. V-Groove Butt Joint designs are frequently welded with FCAW and SAW in combination. Weld shrinkage data was collected for each of these processes.
- 1.4.3 **Method Of Application** - Welding processes implemented are identified by the type of power source (manual, semi-automatic, and automatic). Applications on backing versus no backing or one-sided welding versus two-sided welding are examples of different application methods that are identified among the common attributes of a shrinkage data set.
- 1.4.4 **Joint Position** - Shrinkage data was collected in either of three positions, flat, vertical or horizontal. Shrinkage data collected in the first and second interim processes was from the flat position and all three joint positions in the third interim process. The overhead position was not overlooked, but shrinkage factors for this position are not included because of the limited collection of shrinkage data.
- 1.4.5 **Material Weight** - Shrinkage data is organized by material weight groups. See chart below for the corresponding relationship between material weight and plate thickness.

WEIGHTS IN LBS PER SQUARE FEET	MATERIAL THICKNESS (INCHES)
10.20	1/4
15.30	3/8
20.40	1/2
25.50	5/8
30.60	3/4
35.70	7/8
40.80	1
45.90	1 1/8

-Figure 1-4-

1.4.6 Independent Variables - Factors that affect the degree of weld shrinkage within each interim process data set are the independent variables. These variables change as a result of the working conditions and decisions made by the welding operator. Each of these variables influence shrinkage independently.

1.4.6.1 Welding Parameters - From the welding parameters, voltage, amperage, and travel speed, the heat input of the welding process is calculated. In several applications the welding parameters are adjusted to specified settings by the weight of the material.

1.4.6.2 Joint Gap - This independent variable determines the weld size for a given material thickness. For a given joint design, the amount of weld metal required to fill the joint is determined by this changing attribute.

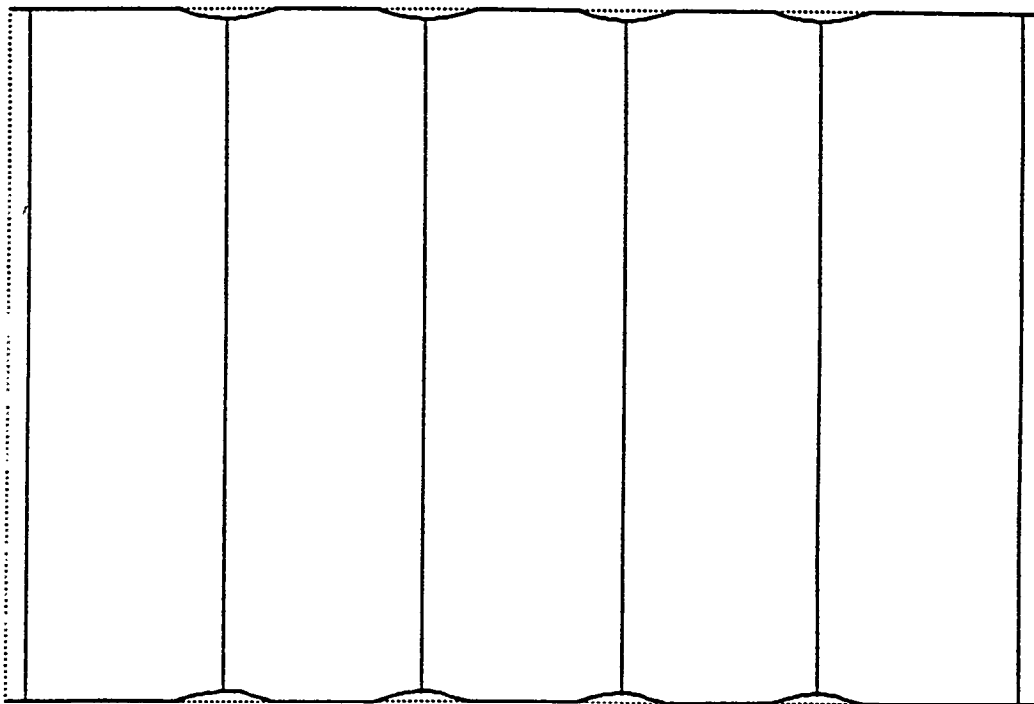
1.4.6.3 Plate Temperature - The difference in base material temperatures recorded at the pre-weld measurement times and the post-weld measurement times is critical for the second interim process. Thermal plate movement from ambient temperature change, if not accounted for, can produce dimensional changes that are as great as the weld shrinkage. To account for this plate expansion or contraction factor, allowances are provided depending upon the plate temperature gradients (Figure 3-1). Block movement resulting from ambient temperature changes, is caused by thermal expansion and contraction. The pre-weld measurement of a butt joint can shift through the day as a result of ambient temperature changes.

1.4.6.4 Restraint Conditions - The amount of weld joint shrinkage is dependant upon the level of joint restraint. Different forms of restraint counteract the shrinkage forces of a joint being welded. The most obvious form of joint restraint is created by the joint fitting aids. For a V-Groove butt joint for example, reducing the number of strongbacks will lessen the restraint conditions creating more allowance for shrinkage. Experimental test results given in this report confirm the spread of weld shrinkage in restraint and no restraint conditions. In the third interim process there are other forms of restraint, more complex that also affect block movement or weld shrinkage.

2.0 FIRST INTERIM PROCESS - PLATE PANEL BUTT SHRINKAGE:

A welded butt joint between two (2) plates shrinks both transversely and longitudinally changing the dimensions of the plate. Figure 2-1 illustrates these two (2) types of panel shrinkage, with shrinkage in the longitudinal direction causing panel bowing, and shrinkage in the direction transverse to the welded joints causing loss of panel width. Transverse panel shrinkage is the cumulative shrinkage of all the individual joints.

The panel bowing condition is not included in the report because loss to the longitudinal panel edge length does not occur. Instead panel bowing is a localized distortion as indicated by the diagram.



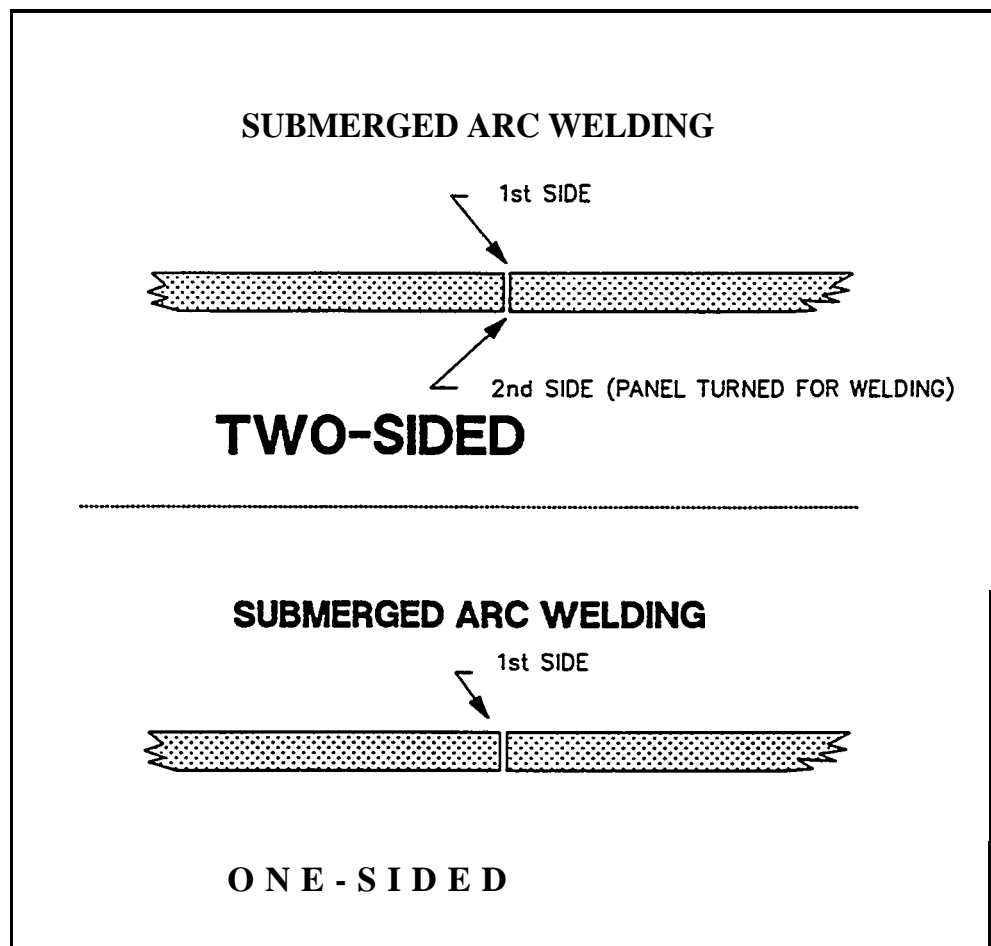
PANEL ASSEMBLY SHRINKAGE

- Figure 2-1-

Transverse shrinkage was measured at three (3) typical locations along the joint length. Shrinkage measurement locations were common for all of the joints recorded. Pre-weld measurement locations were placed at both ends of the joint, 200mm from the panel edge and one (1) measurement at the mid-length of the joint. The pre-weld measurement was recorded together with the joint gap at each location.

2.1 JOINT DESIGN - SQUARE BUTTS:

Among the butt joint designs used for assembly of plate panels, the most common is the square butt. Square butt joints are welded with one process, Submerged Arc Welding, using two (2) methods of application. These methods are described as a one-sided welding application and a two-sided welding application (Figure 2-2). With both applications the joint position is flat. The range of material thicknesses for the square butt joint design is limited and is indicated for each application.



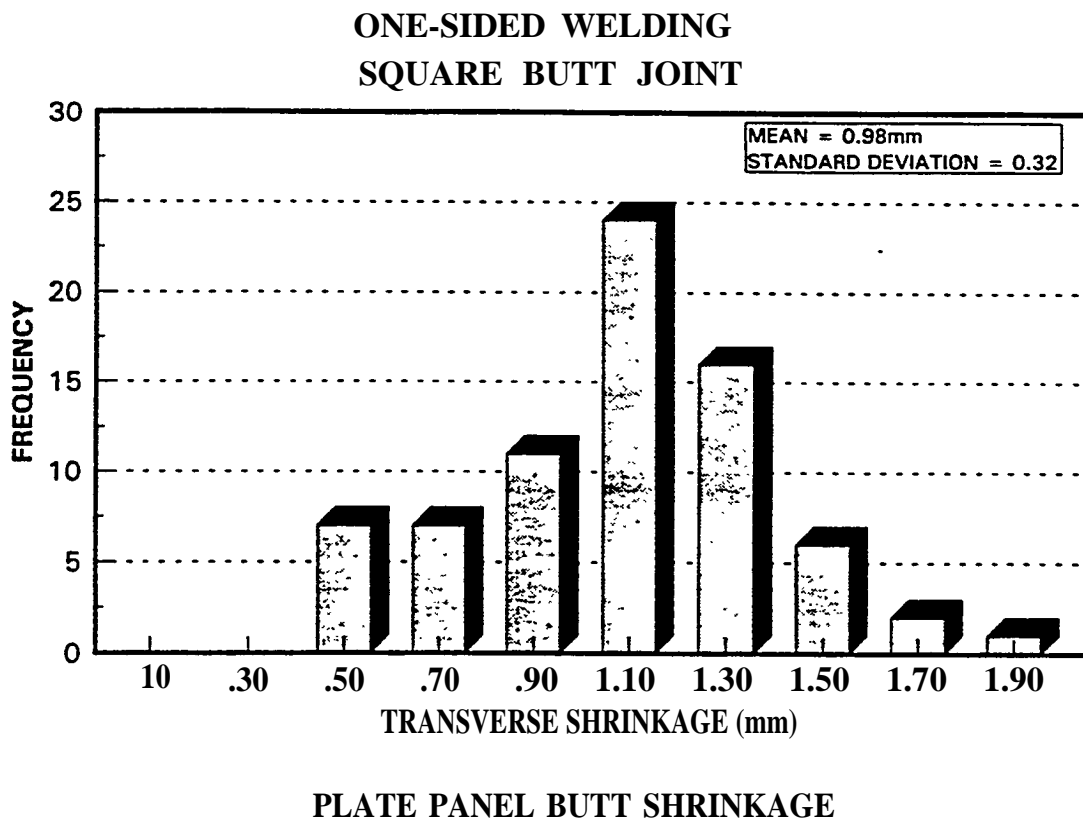
WELDING APPLICATIONS FOR SQUARE BUTT JOINTS

- Figure 2-2-

2.1.1 One-Sided Welding - One-sided describes the method of welding application. With the panel joint positioned on a fluxed copper backing bar a full penetration weld is accomplished from one side of the joint, with one pass.

The full collection of shrinkage data from this method of welding application is displayed in the histogram below (Figure 2-3). The horizontal axis represents the transverse shrinkage range with 0.20mm cell widths and is labeled using the mid-points of each 0.20mm cell. The number of transverse shrinkage measurements that fall within each cell is given by the frequency on the vertical axis. The most common transverse shrinkage measurement recorded for this process as the bar chart illustrates falls within the 1.00 mm to 1.20 mm cell. A total of 24 shrinkage measurements fall within this range.

Before the spread of shrinkage is analyzed with respect to the independent variables, the histogram provides a preliminary analysis of the magnitude and range of data.



- Figure 2-3-

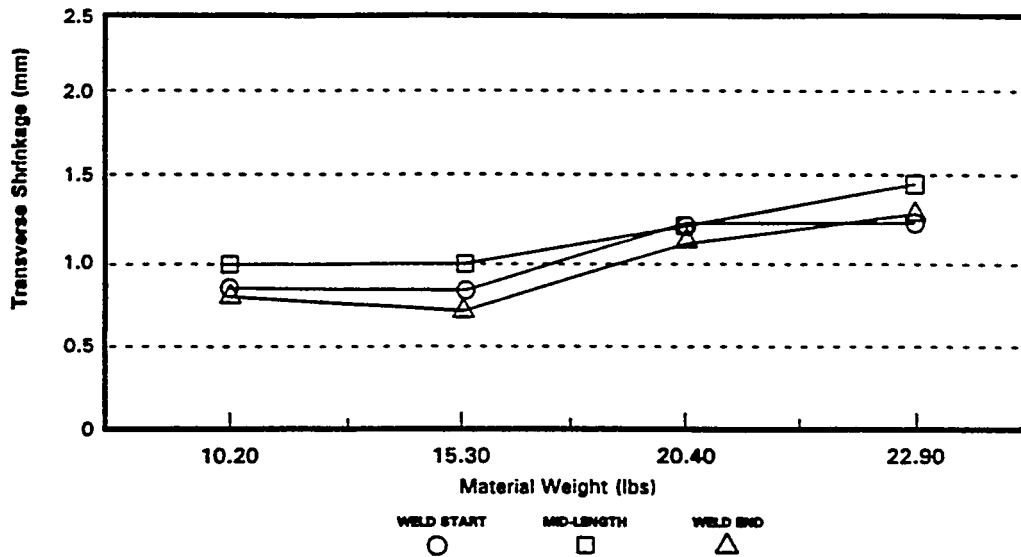
Material Thickness - The data tables of shrinkage measurements grouped by material weight are given on pages 18 and 19. The mean shrinkage and standard deviation is computed for each material weight group. Note in each case that the standard deviation computed is less than the standard deviation calculated from the full data set. Material weights greater than 22.90 lbs were not fabricated with this process, at the time of this study.

MATERIAL WEIGHT (LBS.)	10.20	15.30	20.40	22.90
MEAN TRANSVERSE SHRINKAGE	0.88mm	0.82mm	1.19mm	1.36mm
STANDARD DEVIATION	0.24	0.21	0.16	0.30
JOINT GAP BY DESIGN (mm)	0.00	0.00	0.00	3.00

Before analysis of the independent variables, shrinkage variability is examined to determine the relative shrinkage levels at each of the three joint locations. The three joint locations shrinkage data represents are the Weld Start, Mid-Length, and Weld End Locations. The spread of mean shrinkage calculated for each joint location is illustrated in Figure 2-4, by each material weight group. If data bases of equal and sufficient sizes were available for each material weight group, a standard deviation of equivalent proportions would provide a realistic comparison of the shrinkage spread at the three joint locations.

This graph illustrates greater shrinkage values at the mid-length location of the joint, but this pattern is not typical of joints that have no pre-weld joint gap (pages 18 and 19). Joint shrinkage with gaps 0.5mm and less in the 10.20 lb. data set does not fluctuate between locations more than 0.06mm.

FLAT PANEL SQUARE BUTTS



MEAN TRANSVERSE SHRINKAGE BY
MATERIAL WEIGHT GROUPS AND JOINT LOCATION

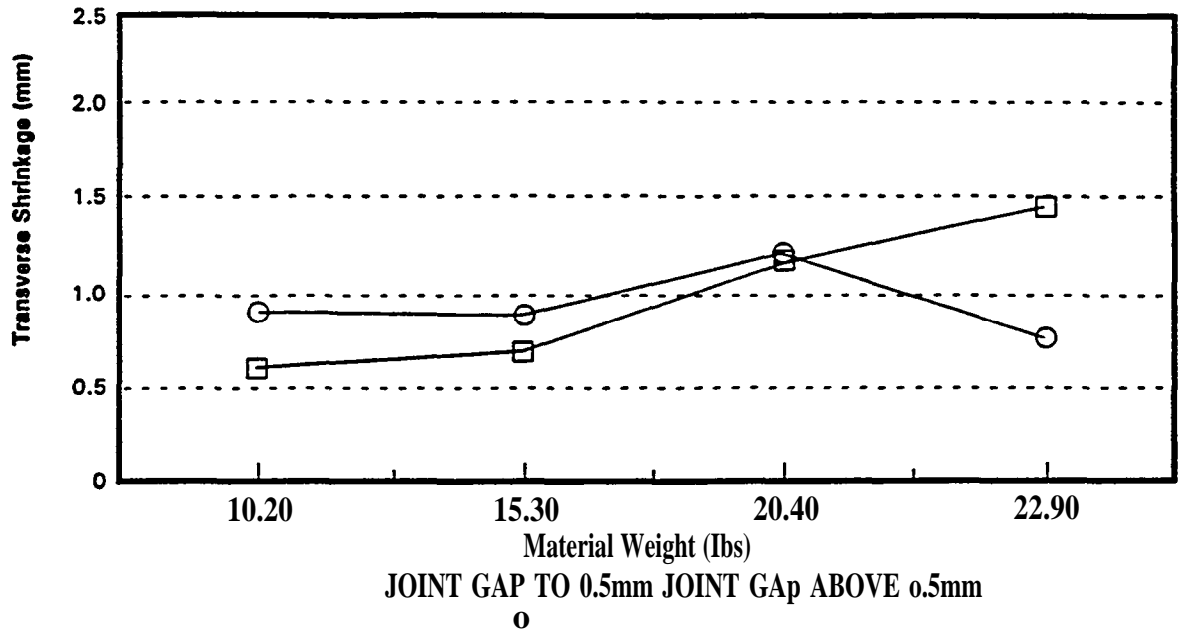
- Figure 2-4 -

Independent Variables - Understanding the causes of the shrinkage variability within the data set, continues by the breakdown of shrinkage data according to the independent variables of the welding process.

The welding heat input is one independent variable that can be changed by individual joint. With this one-sided process, the heat-input is set based on the material thickness being welded. The heat-input does not change randomly but remains in a fixed range.

Another independent variable is the pre-weld joint gap which determines the weld joint area for a given material weight group (Figure 2-5). Each location where pre-weld shrinkage data was gathered, the joint gap was registered at typical levels of 0 and 0.5 millimeters. Two (2) and three (3) millimeter root gaps were excessive and uncommon for material weights below 22.90 lbs..

FLAT PANEL SQUARE BUTTS



TRANSVERSE SHRINKAGE PER JOINT ROOT GAP

- FIGURE 2-5-

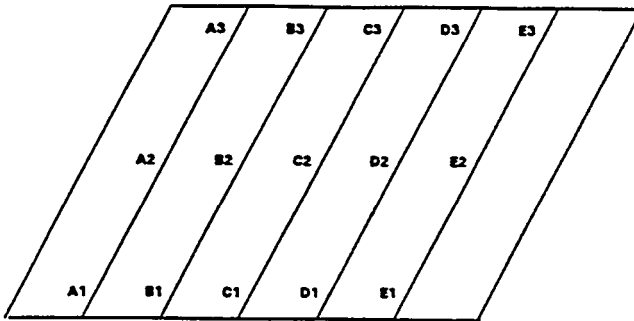
Transverse shrinkage is small and seemingly insignificant, but when considering the number of plates per panel, the transverse shrinkage of butts becomes cumulative. In Figure 2-6 the cumulative joint shrinkage calculated from each of the panel butts is shown for the Weld Start, Mid-Length, and Weld End Locations. The shrinkage of each location is identified by a letter and number.

Joint Design:**Square Butt****Process****SAW****Method of Application**Automatic. One sided Welding
with Fluxed Copper Backing Bar**Position of Welding**

Flat

Material Weight (lbs.)

10.20

Independent VariablesHeat Input
Joint gap**Transverse Shrinkage (mm)**

LOCATION	A+	B+	C+	D+	E =	Cumulative Shrinkage (mm)
Weld Start - 1	0.56	0.50	0.76	0.80	0.41	3.03
Mid-Length- 2	0.84	0.76	1.04	1.07	0.70	4.41
Weld End -3	0.43	0.53	0.61	1.06	0.50	3.15

CUMULATIVE SHRINKAGE OF PANEL JOINTS BY EACH LOCATION

-Figure 2-6-

MULTIPLE REGRESSION OF TRANSVERSE SHRINKAGE!

Regression Analysis - Analysis of the independent variables and their effects on weld shrinkage is apparent through a multiple regression of data. Regression is a measurement of how different factors relate to each other with a group of numbers that represent the numeric relationships between the variables. Here the relationship of the independent variables (factors) with the dependent variable, weld shrinkage is analyzed.

INDEPENDENT VARIABLES			DEPENDENT VARIABLE
			I
JOINT LOCATION	MATERIAL WEIGHT (mm)	JOINT GAP	WELD SHRINKAGE

The first independent variable is included to identify the location at which the shrinkage measurement was recorded, either of three locations, weld start, mid-length, or weld end locations*

The next variable in the regression analysis is the material weight group which represents one of the joint sizes, either 10.20 lbs., 15.30 lbs., 20.40 lbs., or 22.90 lbs..

One variable shown, the joint gap, is consistently 0.5mm or less with exception of the 22.90 lb. group. This size of joint gaps were most consistent in this range, so the variable is not included in the regressions.

The welding heat input (calculated from the welding parameters) is not included because this variable is adjusted to a specified setting based on the weight of material. This variable is changed relative to the weight of material only and so is not needed in the regression.

ONE SIDED WELDING REGRESSION RESULTS:

●	Constant	=	054001	
Ž	Standard Error of Y Estimate	=	024334	
Ž	RSquared	=	034640	
Ž	Number of Observations-	=	73	
Ž	Degrees of Freedom	=	70	
			<u>MATERIAL</u>	<u>JOINT</u>
			<u>THICKNESS</u>	<u>LOCATION</u>
Ž	X Coefficient	=	0.03345	-0.0267
Ž	Standard Error of Coefficient	=	0.005634	0.03477

Using these regression results the predicted shrinkage factor is given for the material weight thickness groups.

ONE-SIDED SQUARE BUTT REGRESSION ANALYSIS

PREDICTED SHRINKAGE

The predicted shrinkage of each material weight group is shown for the common joint gap sizes.

MATERIAL WEIGHT, 10.20 LBS.
(All measurements in millimeters)

JOINT GAP	SHRINKAGE
0	0.80
1.0	0.90

MATERIAL WEIGHT, 15.30 LBS

JOINT GAP	SHRINKAGE
0	0.90
1.0	1.10

MATERIAL WEIGHT, 20.40 LBS.

JOINT GAP	SHRINKAGE
0	0.9
1.0	1.1
2.0	1.2

MATERIAL WEIGHT, 22.90 LBS.

JOINT GAP	SHRINKAGE
0	0.9
1.0	1.1
2.0	1.2
3.0	1.3

PANEL SHRINKAGE DATA

JOINT DESIGN: SQUARE BUTTS

PROCESS: SAW

METHOD OF APPLICATION: ONE-SIDED WELDING

MATERIAL WEIGHT, 10.20 LBS.

PRE-WELD JOINT GAP AND SHRINKAGE (mm)

PANEL ID #	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES)
42205B	0.0	1.07	0.0	0.80	0.0	0.90	87,500
43501D	0.0	0.80	0.0	1.07	0.0	1.06	
31101A	0.5		0.0	1.12	0.0	0.52	
32101B	0.0	0.98	0.0	1.07	0.0	1.23	
32101A	0.5	1.12	0.0	1.02	0.0	1.05	
43501C	0.0	0.76	0.0	1.04	0.5	0.61	
42205A	0.0	1.12	0.5	1.09	0.5	0.90	
43501A	0.5	0.56	1.0	0.84	0.5	0.45	
43501E	1.0	0.41	0.0	0.70	0.5	0.50	
43501B	1.0	0.50	0.0	0.76	0.0	0.53	

MATERIAL WEIGHT, 15.30 LBS.

PRE-WELD JOINT GAP AND SHRINKAGE (mm)

PANEL ID #	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES)
35602A	0.0	1.09	0.0	1.01	0.0	0.79	96,000
35602B	0.0	0.70	0.0	1.07	0.0	0.83	
26101A	0.0	0.47	0.0	1.06	1.0	0.62	
35602C	1.0	0.85	0.5	0.89	0.5	0.47	

PANEL SHRINKAGE DATA
PROCESS: SAW
METHOD OF APPLICATION: ONE-SIDED WELDING

MATERIAL WEIGHT, 20.40 LBS.

PRE-WELD JOINT GAP AND SHRINKAGE (mm)

PANEL ID #	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES)
30301A	0.0	1.17	0.0	1.20	0.0	1.27	136,500
32900A	0.0	1.27	0.0	1.44	0.0	1.22	
30302A	0.0	1.05	0.0	1.30	2.0	1.16	
23301B	1.0	1.13	0.0	0.90	1.0	0.66	
23301A	0.5	1.21	1.0	1.07	0.5	1.12	
32903A	1.0	1.25	0.0	1.26	2.0	1.44	
35301A	1.0	1.37	1.0	1.28	0.5	1.20	
35302A	3.0	1.13	1.0	1.27	1.0	1.07	

MATERIAL WEIGHT, 22.90 LBS.

PRE-WELD JOINT GAP AND SHRINKAGE (mm)

PANEL ID #	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES)
27901B	3.0	1.01	3.0	1.33	0.5	0.77	168,000
27903A	2.0	1.51	2.0	1.51	3.0	1.47	
27901A	3.0	1.26	3.0	1.56	3.0	1.34	

2.1.2 Two-Sided Welding - This welding application is described as two-sided because the panel is turned to weld the second side. Unlike one-sided welding, full penetration from one side is not required because full joint fusion will be achieved on the second side. Only one welding pass is required for each side of the joint with no back-gouging.

Shrinkage data measurements are grouped in the respective cell widths and displayed in the histogram (Figure 2.7). The horizontal axis is labeled with the mid-points of each 0.20mm cell. The greatest frequency of shrinkage falls within the 0.60 to 0.80mm cell range. The mean shrinkage and variability within the data set are shown below.

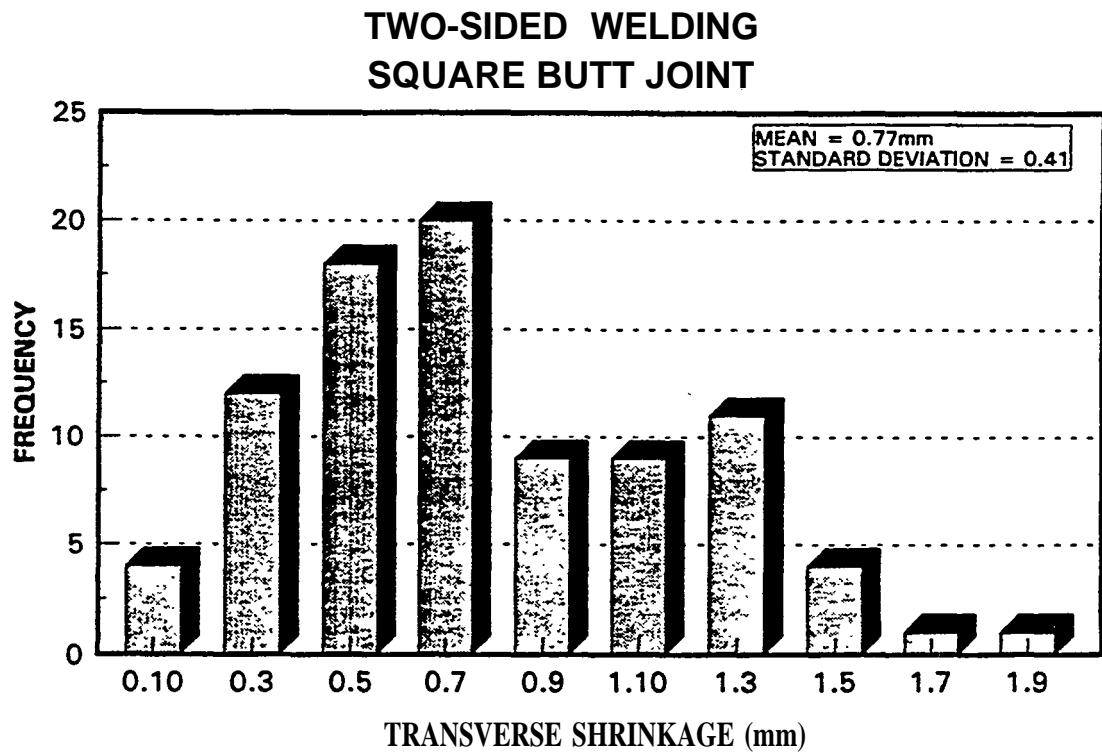


PLATE PANEL BUTT SHRINKAGE

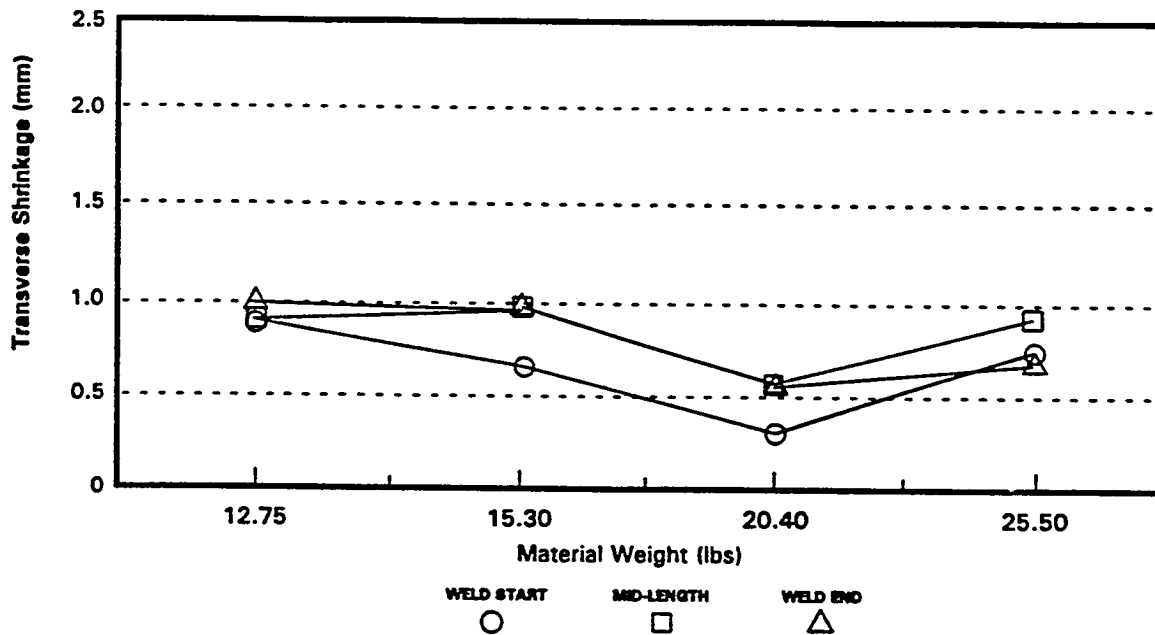
- Figure 2-7-

Material Thickness - The data tables of shrinkage measurements grouped by material weight are given on pages 26 and 27.

MATERIAL WEIGHT (LBS.)	12.75	15.30	20.40	25.50
MEAN TRANSVERSE SHRINKAGE	0.94mm	0.86mm	0.46mm	0.79mm
STANDARD DEVIATION	0.37	0.42	0.23	0.41
JOINT GAP BY DESIGN (mm)	0	0	0	0

Variability of shrinkage measurements is examined with respect to the three joint locations. The shrinkage spread between each of the joint locations, is illustrated in Figure 2-8.

FLAT PANEL SQUARE BUTTS



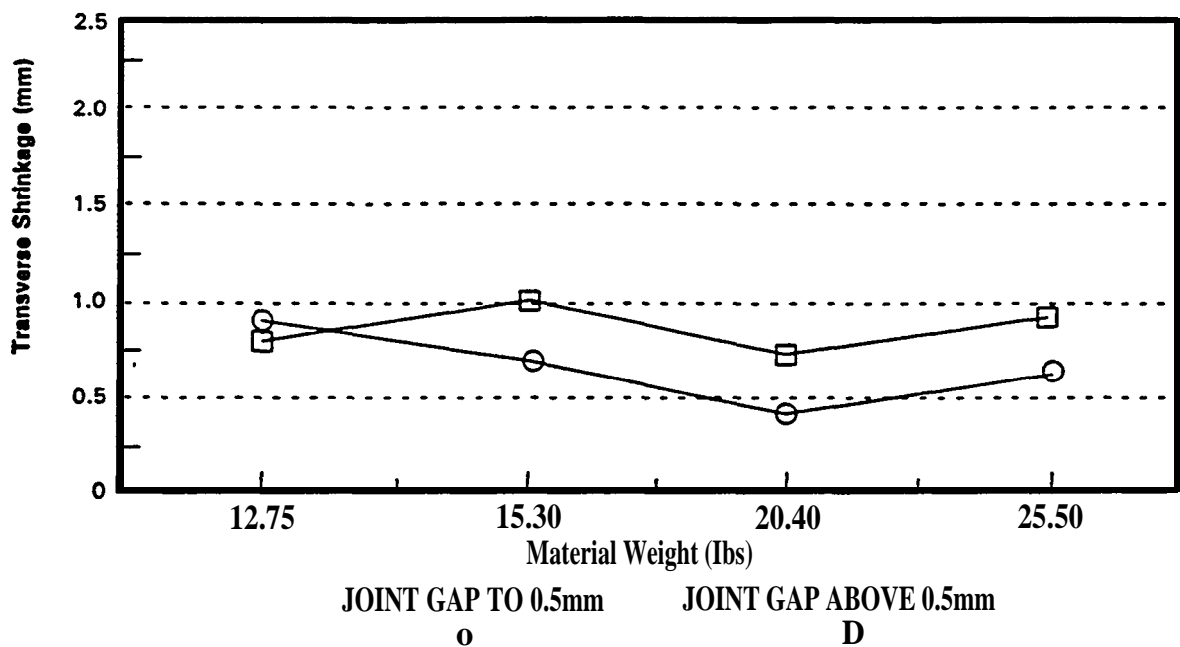
MEAN TRANSVERSE SHRINKAGE BY
MATERIAL WEIGHT GROUPS AND JOINT LOCATION

-Figure 2-8-

Independent Variables - The lower welding heat input characteristic of this process in comparison with one-sided welding produces lower base metal dilution. After the first side is welded, a restraint condition now exists against further shrinkage, when the second side is welded. This is in contrast with one-sided welding which is run with higher heat inputs for a full penetration weld from one-side. The welding heat-input is again unique to each material weight group.

Unlike transverse shrinkage in one-sided welding, average shrinkage drops with the increasing material weight groups. The decline in shrinkage is most evident for the 20.40 lb. material. Correlation of the pre-weld joint gap with transverse shrinkage is analyzed (Figure 2-9) and the significance of this variable on transverse shrinkage is evident. Further analysis is required to study the effects of pre-weld gap on shrinkage levels at each material weight group.

FLAT PANEL SQUARE BUTT'S



TRANSVERSE SHRINKAGE PER JOINT ROOT GAP

- Figure 2-9-

MULTIPLE REGRESSION OF TRANSVERSE SHRINKAGE:

Regression Analysis-The same independent variables used for the one-sided regression are used here, with inclusion of the joint root gap.

INDEPENDENT VARIABLES			DEPENDENT VARIABLE
JOINT LOCATION	MATERIAL WEIGHT (mm)	JOINT GAP	WELD SHRINKAGE

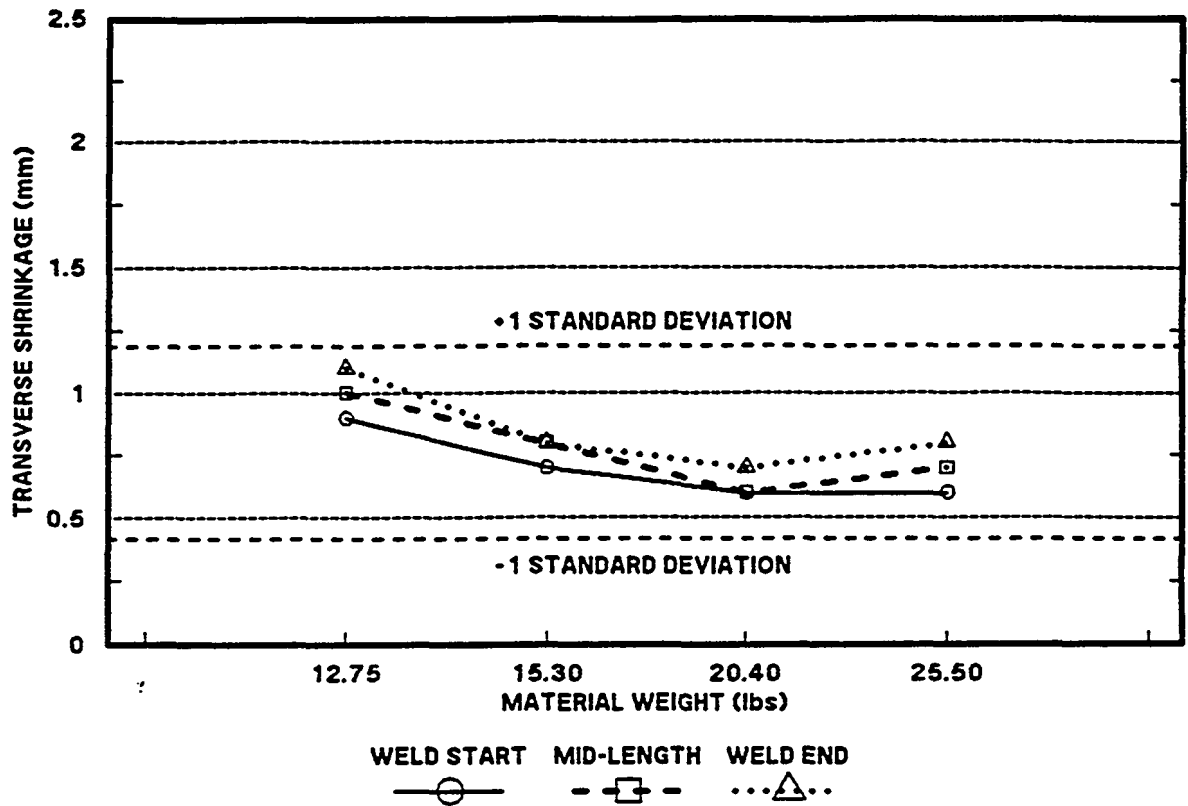
TWO-SIDED WELDING REGRESSION RESULTS:

- Constant = 0.953302
- Standard Error of Y Estimate = 0.383181
- R Squared = 0.157595
- Number of Observations = 77
- Degrees of Freedom = 73

- | | | | | |
|---------------------------------|---|---------------------------|---------------------------|-----------------------|
| | | <u>MATERIAL THICKNESS</u> | <u>PRE-WELD JOINT GAP</u> | <u>JOINT LOCATION</u> |
| • X Coefficient | = | - 0.023005 | 0.166469 | 0.078682 |
| • Standard Error of Coefficient | = | 0.009160 | 0.066276 | 0.054170 |

Using these regression results the predicted shrinkage factor is plotted by the material weight thickness groups using the average preweld joint gap from the data set rounded off to the nearest millimeter. (Figure 2-10)

PREDICTED SHRINKAGE:



PLOTTED REGRESSION RESULTS

PANEL SHRINKAGE - TWO-SIDED SQUARE BUTTS

INDEPENDENT VARIABLES

MATERIAL WEIGHT (LBS)	AVERAGE JOINT GAP
12.75	1.0
15.30	0.0
20.40	0.0
25.50	1.0

- Figure 2-10 -

TWO-SIDED SQUARE BUTT REGRESSION ANALYSIS

PREDICTED SHRINKAGE

The predicted shrinkage of each material weight group are shown for the common joint gap ranges.

MATERIAL WEIGHT, 12.75 LBS.
(All measurements in millimeters)

JOINT GAP	SHRINKAGE
0	0.8
1.0	0.9

MATERIAL WEIGHT, 15.30 LBS.

JOINT GAP	SHRINKAGE
0	0.8
1.0	0.9

MATERIAL WEIGHT, 20.40 LBS.

JOINT GAP	SHRINKAGE
0	0.6
1.0	0.8

MATERIAL WEIGHT, 25.50 LBS.

JOINT GAP	SHRINKAGE
0	0.5
1.0	0.6

PANEL SHRINKAGE DATA

JOINT DESIGN: SQUARE BUTTS

PROCESS: SAW

METHOD OF APPLICATION: TWO-SIDED WELDING

MATERIAL WEIGHT, 12.75 LBS.

PRE-WELD JOINT GAP AND SHRINKAGE (mm)

PANEL ID #	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES) 1ST PASS/2ND PASS
29301A	0.0	1.38	0.5	1.58	0.0	1.74	26,250/30,625
29401A	1.0	1.36	0.0	0.84	0.0	0.57	
44401A	0.0	0.69	0.5	0.70	0.5	0.55	
16301A	0.5	0.94	0.5	1.27	0.5	1.28	
16301B	0.5	0.89	0.5	0.72	0.5	1.29	
16301C	0.5	0.93	0.5	1.15	0.5	1.36	
40201A	1.0	0.78	0.0	1.06	2.0	1.04	
31409B	0.5	0.31	1.0	0.53	1.0	0.45	
31409A	3.0	0.89	1.0	0.56	0.5	0.43	

MATERIAL WEIGHT, 15.30 LBS.

PRE-WELD JOINT GAP AND SHRINKAGE (mm)

PANEL ID #	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES) 1ST PASS/2ND PASS
24801BD	0.0	0.19	0.0	0.64	0.0	0.72	41,192/45,563
24701A	0.0	0.79	0.0	1.39	1.0	1.93	
24801BC	0.0	0.28	1.0	1.06	0.0	0.63	
24801AB	1.0	0.78	1.0	0.96	0.0	1.01	
314082A	1.0	1.15	1.0	0.75	1.0	0.56	

PANEL SHRINKAGE DATA

JOINT DESIGN: SQUARE BUTTS

PROCESS: SAW

METHOD OF APPLICATION: TWO-SIDED WELDING

MATERIAL WEIGHT, 20.40 LBS.

PRE-WELD JOINT GAP AND SHRINKAGE (mm)

PANEL ID #	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES) 1ST PASS/2ND PASS
24801B2D	0.0	0.19	0.0	0.64	0.0	0.72	46,920/56,885
293042A	0.5	0.31	0.0	0.26	0.0	0.45	
24701B2A	0.0	0.13	0.0	0.35	0.0	0.47	
294041A	1.0	0.50	0.0	0.13	0.0	0.34	
31503A	0.0	0.58	0.0	0.38	1.0	0.64	
24801B2C	0.0	0.28	1.0	1.06	0.0	0.63	
24701B2B	0.0	0.39	1.0	0.79	0.0	0.41	

MATERIAL WEIGHT, 25.50 LBS.

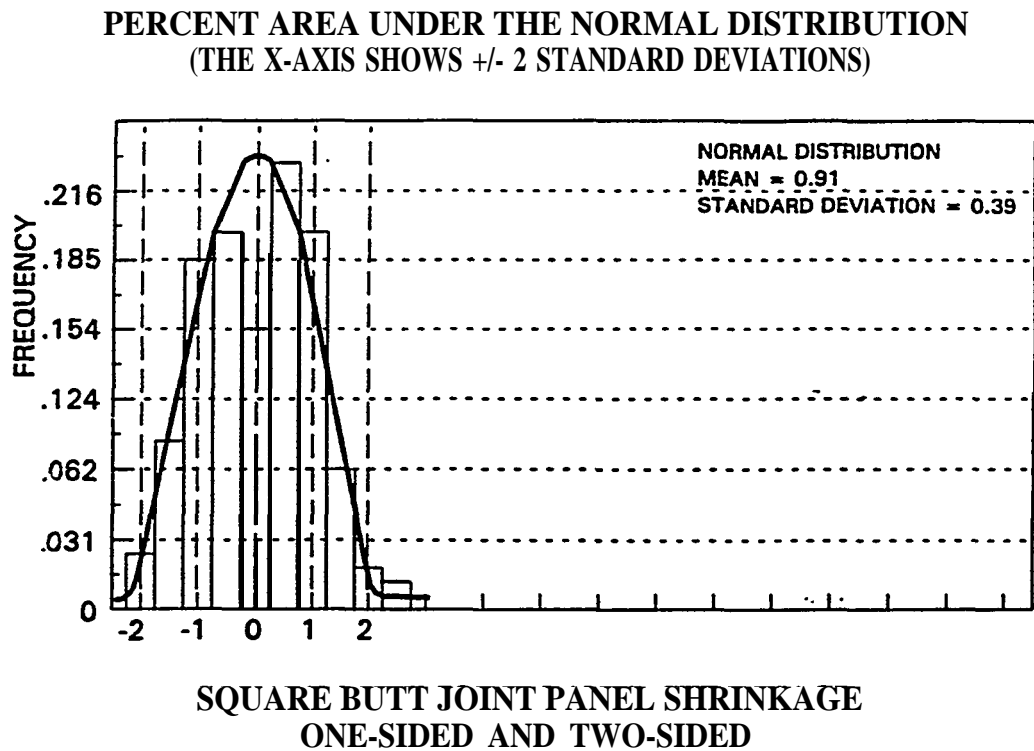
PRE-WELD JOINT GAP AND SHRINKAGE (mm)

PANEL ID #	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES) 1ST PASS/2ND PASS
35201A	0.0	0.24	0.0	0.71	0.0	0.90	73,500/85,658
248104A	0.5	0.31	0.0	0.42	1.0	0.58	
35201A	1.0	0.62	2.0	0.56	4.0	0.55	
36801B	0.5	1.28	1.0	1.57	0.0	0.56	
36801A	3.0	1.29	1.0	1.47	0.0	0.71	

2.2 NORMAL DISTRIBUTION;

All of the data for both the one-sided and two-sided square butt welding applications have been combined to form a complete set of shrinkage data for square butt joint welding.

The data collected for this interim process, when displayed in the density function mathematical model, takes the shape of a bell curve (Figure 2-11) with a 0.91 mm mean shrinkage and 0.39 standard deviation.



- Figure 2-11-

2.3 JOINT DESIGN - V-GROOVE BUTTS:

There are applications for both single V-Groove and double V-Groove joint designs. The single V-Groove is welded with a one-sided application using FCAW on ceramic tile followed with SAW for the fill and cover passes.

The double V-Groove welded with SAW is for a two-sided application. Shrinkage data for this application was not gathered, because there was not a sufficient number of panels to explore these joint designs.

The experimental study of this report does evaluate single V-Groove butt shrinkage, and the range of shrinkage by material weights is evident. V-Groove butt joint shrinkage is included in the third interim process.

WELD SHRINKAGE STUDY:		PLATE PANEL	BLOCK #			
------------------------------	--	--------------------	----------------	--	--	--

PANEL ID			JOINT DIAGRAM
MATERIAL			
THICKNESS			
JOINT DESIGN			
BEVEL			

DIMENSION ID	JOINT GAP	PREWELD MEASUREMENT	POSTWELD MEASUREMENT	SHRINKAGE
TIME/DATE				
PLATE TEMP				

WELDING PROCESS	MANUAL, SEMI-AUTOMATIC	PANEL SIDE	AMPERAGE	VOLTAGE	TRAVEL SPEED	HEAT INPUT

OBSERVATION

DATA SHEET FOR GATHERING DATA

3.0 SECOND INTERIM PROCESS:HULL BLOCK SHRINKAGE

In this process distortion which results from fillet welding stiffeners to panels is analyzed. Panel shrinkage was measured along the panel edge, in directions both longitudinal and transverse to the direction of welded stiffeners. It was not always possible to collect shrinkage data with one common dimension, so shrinkage data is provided with the estimated shrinkage per five (5) meter length.

In the longitudinal stiffener direction the location of the nearest stiffener to the panel edge will produce longitudinal shrinkage. Weld shrinkage in this direction and subsequent loss to panel length is more difficult to determine because of the bowing condition. The areas that have the least bowing, that is the least shrinkage, must be considered together with the other bowed areas.

Taken into consideration with weld shrinkage in the transverse direction was the number of fillets and leg size of welds per measured length. The tucking allowance or out-of-plane distortion is not considered in the measurement of shrinkage in this study. This type of distortion as mentioned earlier, can be controlled by proper welding procedures.

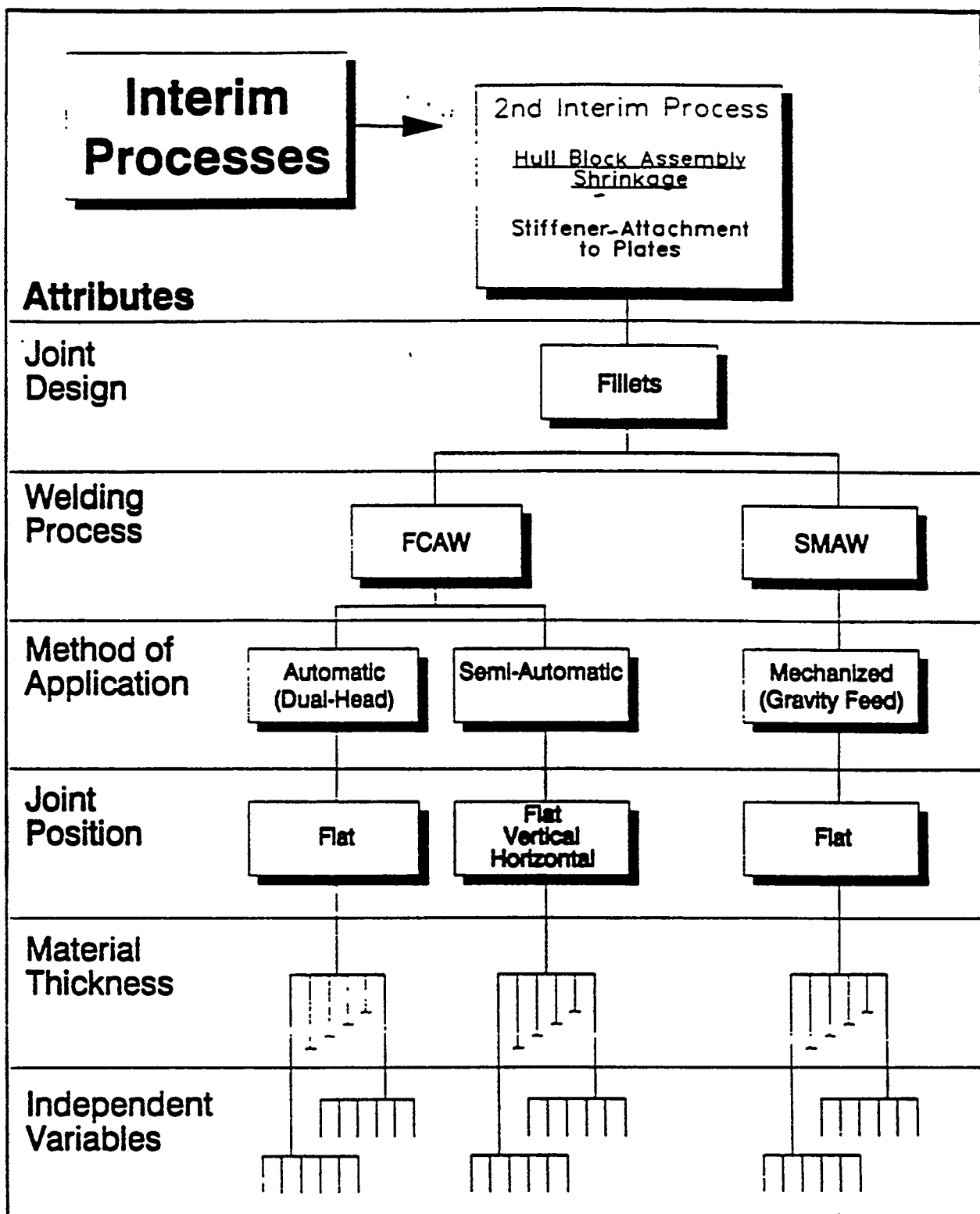
AMBIENT PLATE TEMPERATURE - Thermal plate expansion results from increasing ambient temperature. When determining transverse and longitudinal shrinkage from pre-weld and post-weld measurements, ambient temperatures at both times must be recorded. The dimensional changes resulting from ambient temperature can be as great or greater than the actual weld shrinkage. The opportunities for post-weld measurements were during times the ambient temperature difference was as high as 25 degrees. The coefficient of linear plate expansion was used with calculation of panel shrinkage whenever there was a thermal gradient between measurements. The linear plate expansion chart is given as a reference to the levels of expansion/contraction units, which were used in the adjustments of all data (Figure 3-1).

THERMAL GRADIENT	LINEAR EXPANSION (mm) PER 5 Meters
5°	0.17
10°	0.33
15°	0.50
20°	0.66
25°	0.83
30°	1.00
35°	1.16
40°	1.33
45°	1.49
50°	1.66

- FIGURE 3-1-

3.1 JOINT DESIGN - FILLER

The common joint design used in hull block assembly is the fillet joint. The fillet weld is utilized to join materials on the panel surface. Stresses are created on one side of the panel, which induce panel distortion, resulting from transverse and longitudinal panel shrinkage. This joint design must be distinguished from full penetration T-Joints not included in the evaluation. The flow chart (Figure 3-2) illustrates the breakdown of the 2nd Interim Process.



- Figure 3-2 -

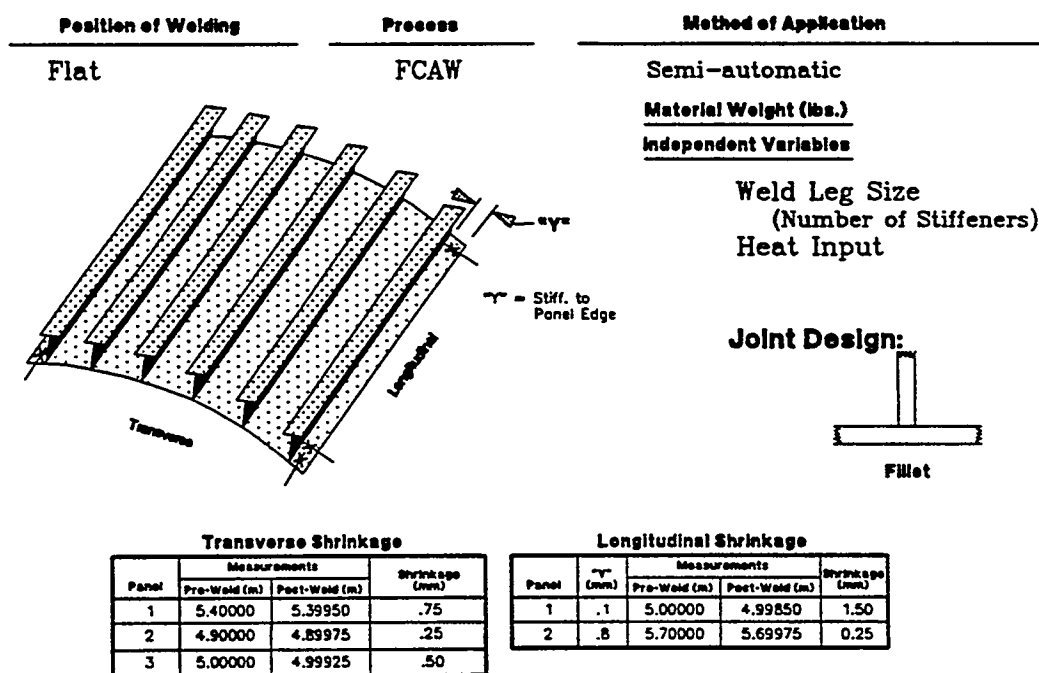
3.2 WELDING PROCESSES AND METHODS OF APPLICATION:

Fabrication of stiffened plate panels is with SMAW (Shielded Metal Arc Welding) and FCAW (Flux-Cored Arc Welding) processes. The SMAW method of application most commonly used, is with the gravity-feed mechanized process. Two methods of application are common with FCAW processes, Semi-automatic and Automatic.

JOINT POSITION - The joint position was flat for all of the collected shrinkage data groups, which the mechanized SMAW, and automatic FCAW process are designed. Out-of-position welding is most commonly performed with semi-automatic FCAW and SMAW (manual). Because of a time factor me allowances for out-of-position welding with those processes have not been **included, although these processes, applications and positions will each produce a new set of shrinkage levels.**

3.2.1 FCAW, Semi-Automatic:

Both transverse and longitudinal panel shrinkage data is provided in Figure 3-3. Longitudinal shrinkage is presented with the "Y" measurement which is the panel edge to nearest stiffener distance. The significance of this value on panel edge shrinkage is shown with the relative shrinkage levels in the chart. With limited data for this process further analysis is not included.



ASSEMBLY UNIT SIDE SHELL PANEL SHRINKAGE

FIGURE 3-3-

Independent Variables - The 2nd Interim Process was evaluated together With these variables.

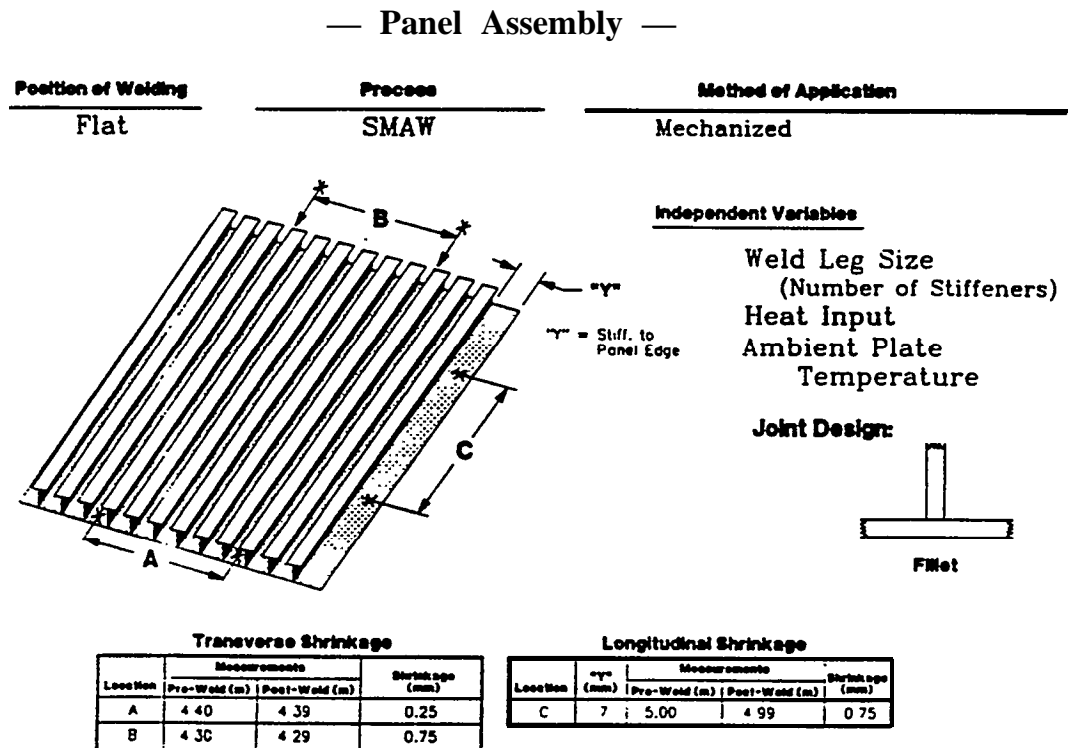
Weld Leg Size : 6.3mm (1/4") (joint Gap=0)
Heat Input: This variable is consistent with in the data set.
Ambient Plate Temperature Thermal gradient

3.2.2 SMAW, Mechanized:

Transverse shrinkage was recorded together with the number of Stiffeners to identify the number of welds per measured length. The shrinkage data set (page 38) provides panel shrinkage in this direction per 5m and this length covers seven (7) Stiffeners.

Longitudinal panel edge shrinkage is dependent upon the proximity of the nearest stiffener to the edge. So allowances for shrinkage must also be based upon this distance.

Figure 3-4 illustrates a typical panel with the attributes identified below, for the transverse and longitudinal panel shrinkage.

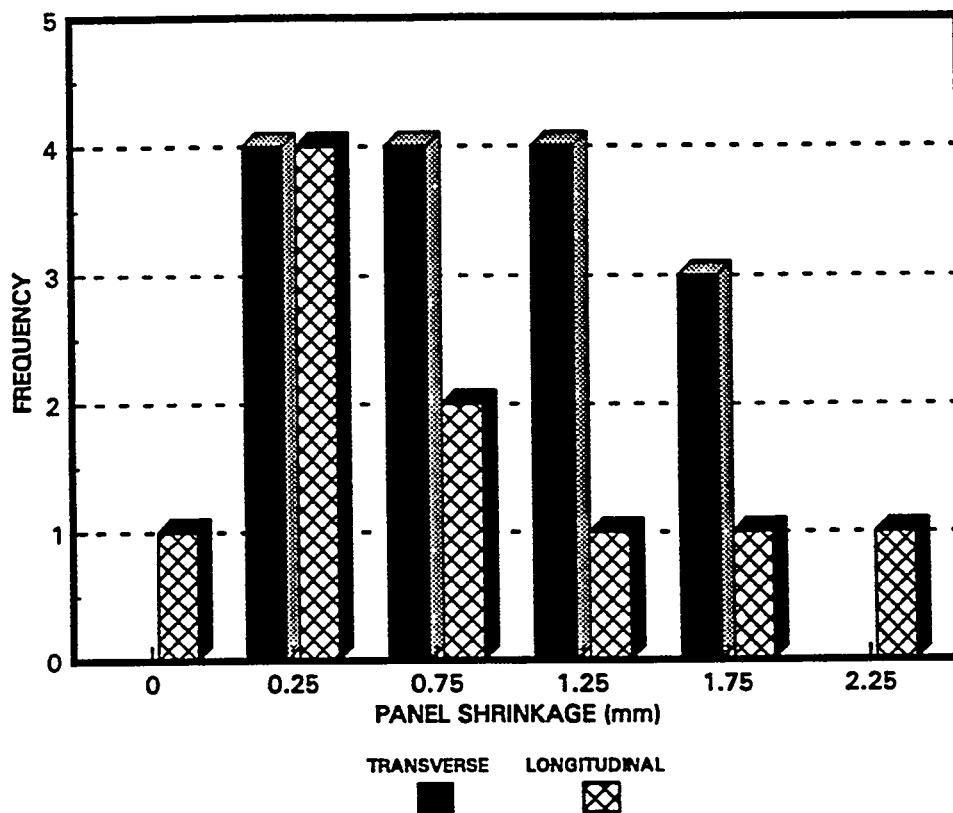


TRANSVERSE AND LONGITUDINAL PANEL SHRINKAGE MECHANIZED, SMAW

- FIGURE 3-4 -

The shrinkage of the full data set is analyzed here with a histogram provided in Figure 3-5.

PANEL WELDING DIRECTION	MEAN (mm)	STANDARD DEVIATION
LONGITUDINAL SHRINKAGE	.89	.38
TRANSVERSE SHRINKAGE	.95	.29



ASSEMBLY PANEL SHRINKAGE, SMAW MECHANIZED

- FIGURE 3-5 -

INDEPENDENT VARIABLES - The fillet weld leg size of 6.3mm (1/4") is a consistent variable in the shrinkage data set. Consistency of application is critical to maintaining this leg size. Leg sizes of 3/16" and 5/16" represent a significant size change and must be analyzed by their respective sizes. Leg sizes will also vary as a result of joint gap, but stiffeners were fit tight under normal conditions.

The weld heat-inputs for each process are not included, because this remains in a freed range dependent upon the size of consumable, and size of weld. The size of consumable was consistent for each panel welded, so the heat input variable remained constant.

Three panels are described here with longitudinal shrinkage results for the nearest stiffeners located at .4m, .7m, and 1.1m from the panel edge. At an edge distance of .4m the longitudinal shrinkage was 1.25mm, but when this distance changed to .7m and 1.1m the panel shrinkage was only 0.25mm.

3.2.3 FCAW, Automatic:

This stiffener welding process is continuous and two-sided (dual-headed). The term continuous refers to the welding application which is continuous, from the start to the end of the joint. The semi-automatic method is not continuous because the operator must start and stop the welding application while proceeding along the joint.

The material weight is a significant attribute because the plate temperature cooling rates will vary by material weights. With a larger database shrinkage data would be grouped by material weight size, but here the shrinkage is analyzed for the full data set.

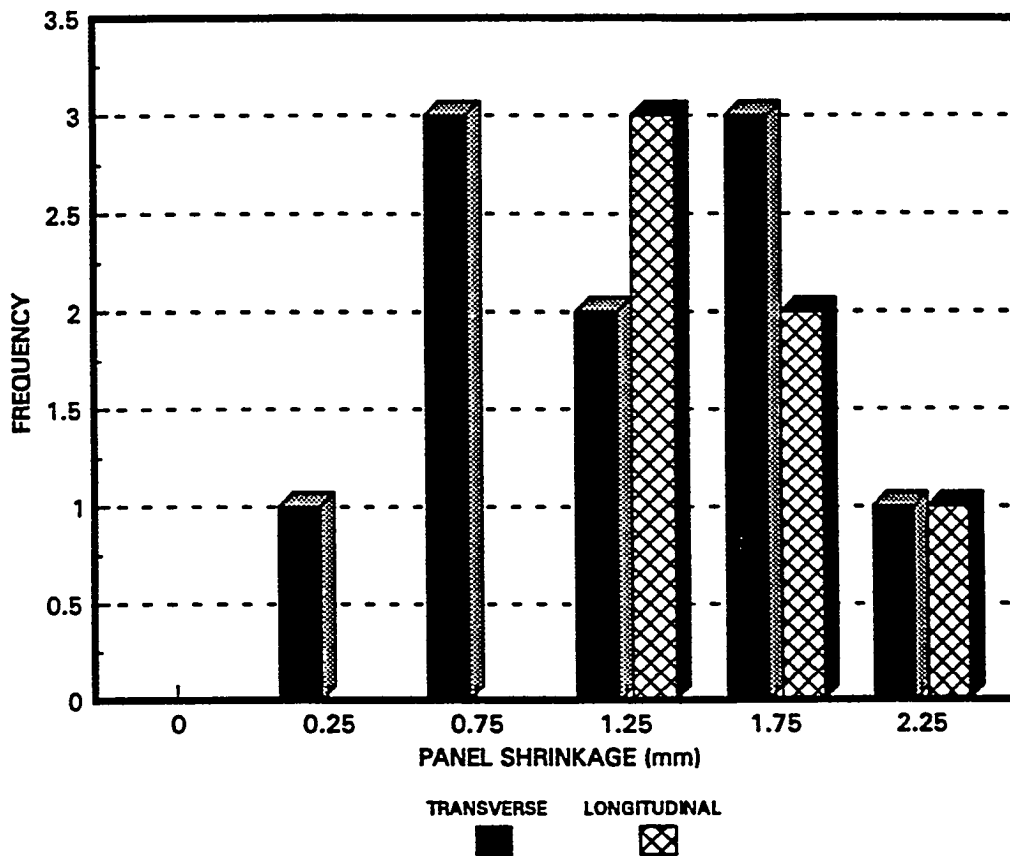
PANEL WELDING DIRECTION	MEAN (mm)	STANDARD DEVIATION
LONGITUDINAL SHRINKAGE	1.43	.22
TRANSVERSE SHRINKAGE	1.51	.40

The histogram (figure 3-6) of this shrinkage is given. The shrinkage data set (page 38) provides panel shrinkage in the transverse and longitudinal direction per 5m.

INDEPENDENT VARIABLES - The fillet weld leg size was 6.3 mm (1/4").

The weld heat-inputs for each process are not included, because this remains in a fixed range dependent upon the size of consumable, and size of weld. The size of consumable never changed, and the heat input remained constant.

With a greater volume of data, more accurate allowances for both transverse and longitudinal weld shrinkage could be made.



ASSEMBLY PANEL SHRINKAGE, FCAW AUTOMATIC

-FIGURE 3-6-

SUB-ASSEMBLY SHRINKAGE DATA

JOINT DESIGN: FILLET
PROCESS: FCAW
METHOD OF APPLICATION: AUTOMATIC

TRANSVERSE PANEL

ASSEMBLY ID #	23819	35901	31606	30302	32901	25301
MATERIAL WEIGHT (LBS)	10.20	10.20	17.85	20.40	20.40	22.90
SHRINKAGE PER 5M (mm)	1.75/0.75	1.37/.97	1.00	1.94/1.66	2.42/2.80	0.39

- Adjusted for thermal gradients between pre-weld and post-weld measurements.
Seven (7) stiffeners per five (5) meter length.

LONGITUDINAL PANEL

ASSEMBLY ID #	23819	35901	35601	30302	32901
MATERIAL WEIGHT (LBS)	10.20	10.20	15.30	20.40	20.40
SHRINKAGE PER 5M (mm)	2.25	1.00 1.00	1.16	1.38	1.83

- Adjusted for thermal gradients between pre-weld and post-weld measurements.

PROCESS: SMAW
METHOD OF APPLICATION: MECHANIZED

TRANSVERSE PANEL

ASSEMBLY ID #	42201	35701	18211	21003	24801	27902	25301	25304	32801	24901	25301
MATERIAL WEIGHT (LBS)	10.20	10.20	12.75	15.30	22.95	22.95	22.95	22.95	30.60	35.70	38.25
SHRINKAGE PER 5M (mm)	1.53	1.42	1.00	0.66 0.66	0.36 0.36	0.4 0.4	1.8	1.21	0.60	1.87 1.49	1.8

- Adjusted for thermal gradients between pre-weld and post-weld measurements.
Seven (7) stiffeners per five (5) meter length.

LONGITUDINAL PANEL

ASSEMBLY ID #	18211	21003	27902	35101	32801	24901	22401
MATERIAL WEIGHT (LBS)	12.75	15.30	22.95	25.50	30.60	35.70	38.25
SHRINKAGE PER 5MM (mm)	0.43 0.86	0.44 0.44	0.00	2.26	1.17	1.90	0.95 0.47

- Adjusted for thermal gradients between pre-weld and post-weld.

4.0 THIRD INTERIM PROCESS - ERECTION JOINT SHRINKAGE

This interim process encompasses the analysis of transverse shrinkage data collected from the primary joints of an erected block unit. Each joint is distinguished by its position and the welding processes and applications implemented. The shrinkage data is classified by each joint type because the attributes of the data sets are unique.

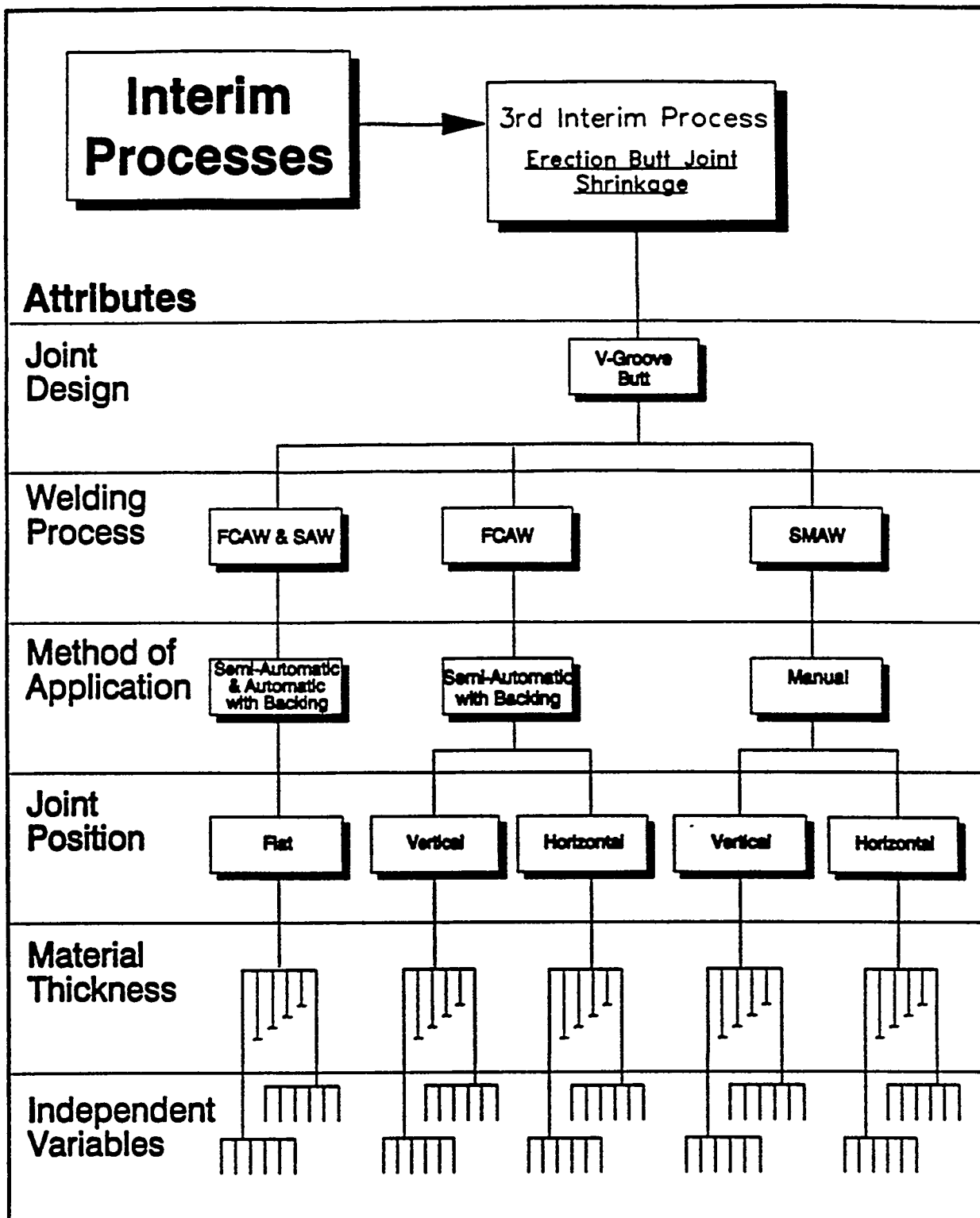
Shrinkage measurement techniques used for gathering data were identical to those used for the f- interim process. Three pre-weld measurements were documented for each joint at the Weld Start, Mid-Length, and Weld End locations together with the joint gap. Weld Start and Weld End measurement locations of erection joints were placed .5 to 1.0 meters from the joint ends.

4.1 Joint Design - V-Groove Butts

The common weld joint design for this process, is the V-Groove Butt with a included bevel angle of 45 degrees that is typically 22.5 degrees per plate and varies between 20 and 25 degrees with no land. The joint bevel, material thickness, and the root gap are used in calculating the joint area. For the purposes of this study the joint bevel is not included in the analysis as a variable because the bevel did not fluctuate more than 10 degrees. By design the root gap is 6.3mm (1/4") as shown in reference of joint design (page 97).

4.2 welding Processes and Methods of Application:

SMAW (manual) or FCAW (semi-automatic) welding processes or a combination of both are used for welding both vertical (shell butts) and horizontal (shell seams) joints. Flat joints (deck seams or butts) were welded with a combination of processes, FCAW (semi-automatic) and SAW (automatic). The one-sided application on ceramic backing was the focus of this study, however, a further study should also include the two (2) sided welding application. The flow chart (page 41) illustrates the breakdown of this interim process into shrinkage data sets by joint Position.

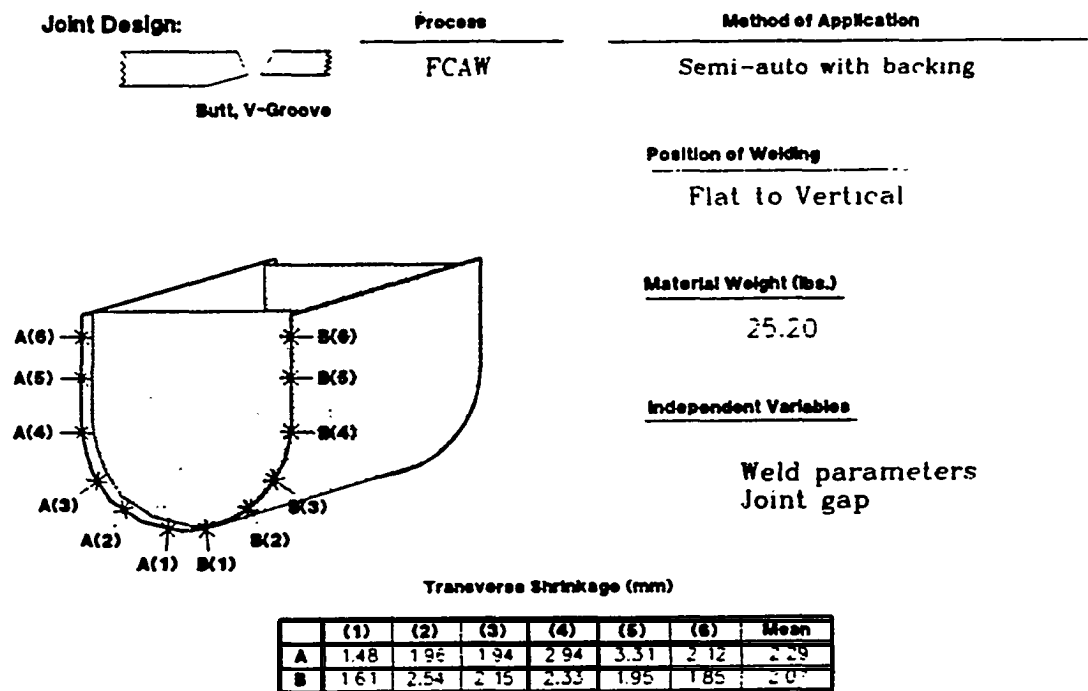


- Figure 4-1 -

4.3 Joint Position:

The geometric positions of weld joints on two types of erection blocks are illustrated in figures 4-2 and 4-3. As a result of the varying degrees of restraint conditions, shrinkage from each type of block cannot be combined although the attributes might be the same. The shrinkage levels shown under each block diagram are an indication of this.

The pre-weld measurements of the bottom shell block were taken with a 2002mm caliper placed across the butt joint in two punch marks, at the location indicated. The same procedure was used after the joint was welded for the post-weld measurements. Shrinkage was calculated at each location from the difference of these two measurements. The shrinkage data is not extensive for bottom shell blocks, due to the stage of construction during the period of this investigation and is therefore not analyzed separately with the shell block shrinkage data.

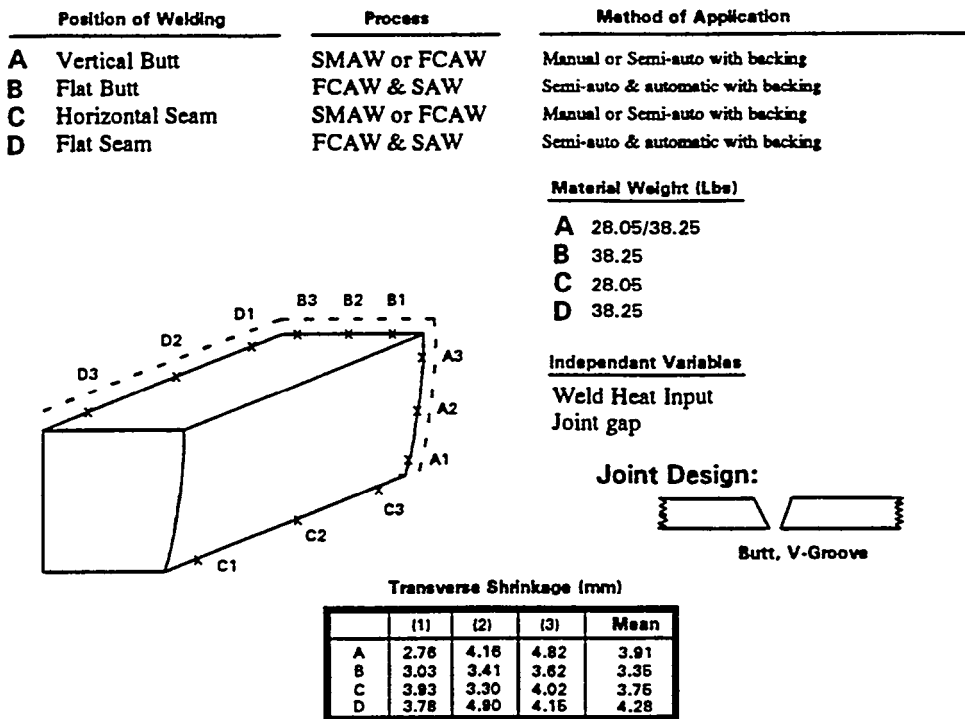


BOTTOM SHELL BLOCK WITH ATTRIBUTES AND JOINT SHRINKAGE DATA

-Figure 4-2-

ILLUSTRATION OF BLOCK WITH WELDING ATTRIBUTES

--SIDE SHELL BLOCK--



SIDE SHELL BLOCK WITH JOINT SHRINKAGE DATA

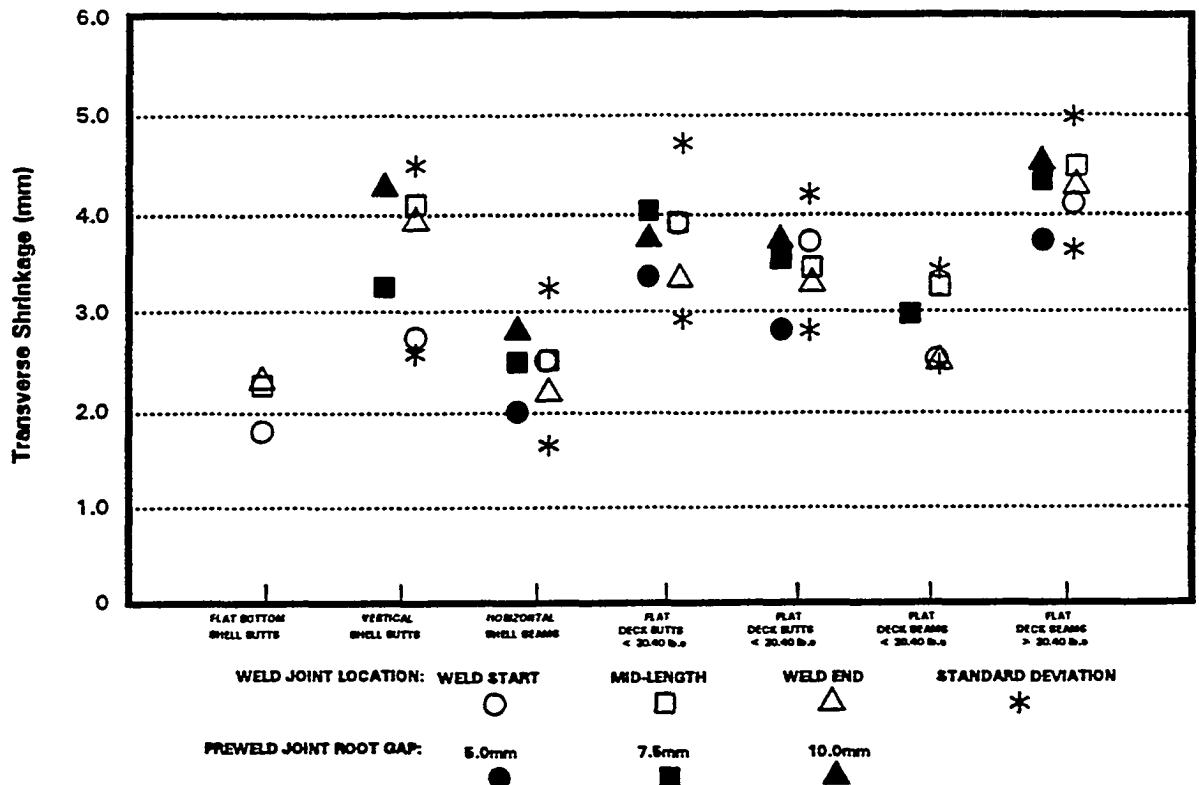
-Figure 4-3-

Figure 4-3 illustrates a side shell block and the four (4) joints with their respective attributes. Pre-weld and post-weld shrinkage data was taken using the same technique with 200mm caliper measurements transverse to the weld direction.

Each joint is classified as its own data set for several reasons. The position of the joint has different forms of outside restraint acting upon it. The types of restraint and spacing also vary. The welding processes and heat-inputs are not common among all of the joint positions.

Side shell blocks are welded in sequence beginning with the shell butt followed by either the shell seam or the deck butt.

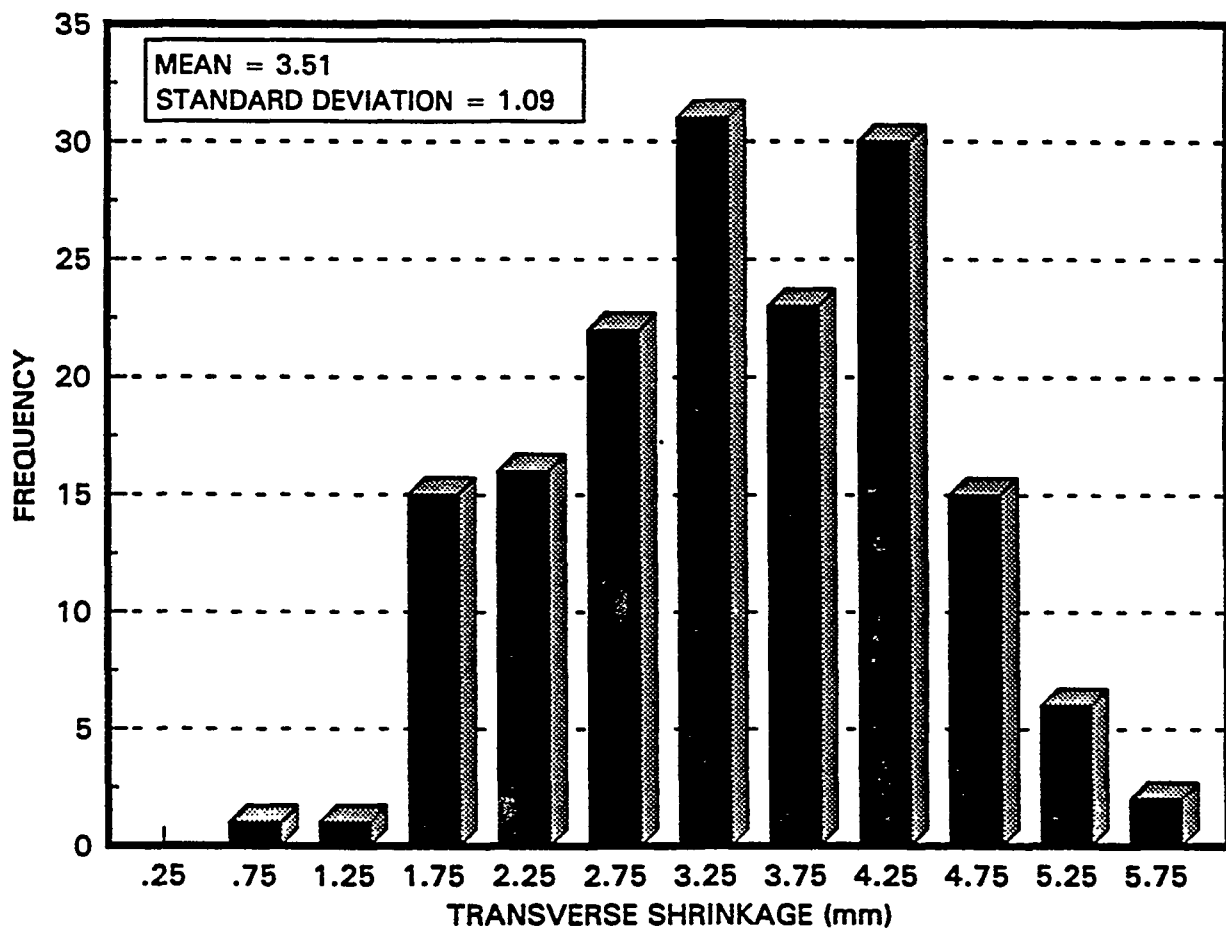
A summarized comparative view of block shrinkage organized by weld joint type is provided in figure 4-4. The range and magnitude of weld shrinkage in each of the data sets is illustrated by the mean values of shrinkage at each joint location and the standard deviation of the full data set. A histogram is provided to show the frequency of shrinkage as an overview which combines all of the weld shrinkage for this interim process. There is further analysis of the data sets by the attributes of the process, as it relates to shrinkage variance, in the following sections.



COMPARATIVE VIEW OF ERECTION JOINT SHRINKAGE DATA SETS BY WELD JOINT TYPE AND LOCATION ALONG THE JOINT LENGTH

-Figure 44-

ALL ERECTION JOINTS



ERECTION JOINT SHRINKAGE HISTOGRAM

- Figure 4-5

4.3.1 VERTICAL SHELL BUTTS:

COMMON WELDING ATTRIBUTES

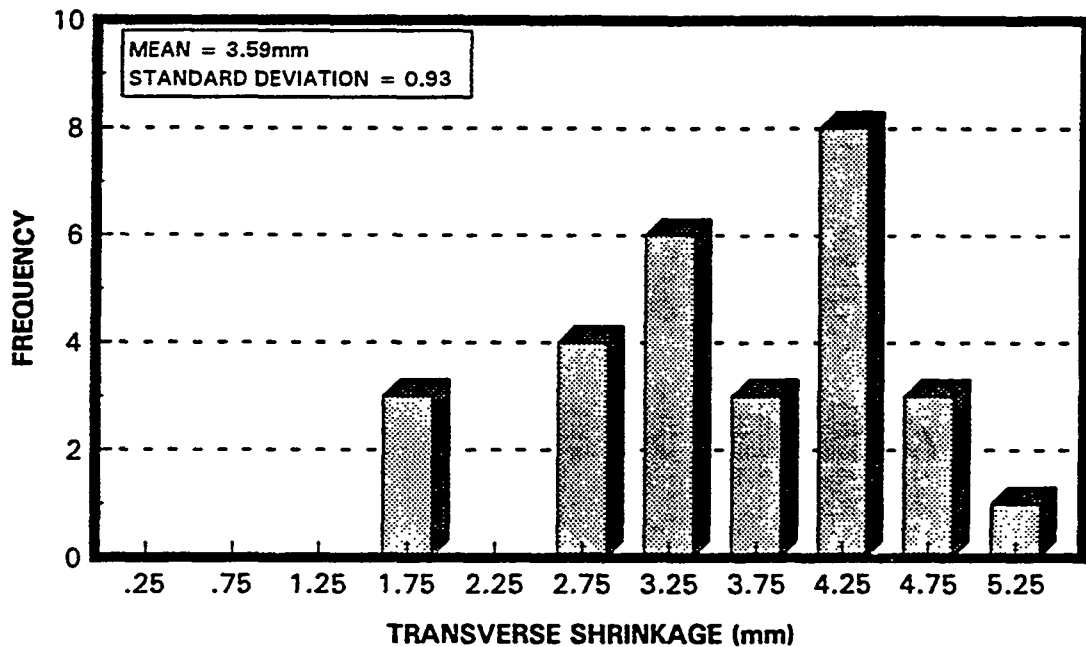
JOINT DESIGN	WELDING PROCESS	METHOD OF APPLICATION	JOINT POSITION
V-GROOVE (45° INCLUDED)	SMAW OR FCAW	MANUAL OR SEMI-AUTOMATIC	VERTICAL

MATERIAL WEIGHT GROUP (LBS)			
22.95	35.70	38.25	40.80

STANDARD WELDING PROCEDURE

Joint Design: Ref. Appendix, Page 97 (see Joint Design B)
Fitting Devices: Slip-type stud fitting aids
Design Joint Gap: 6.3mm

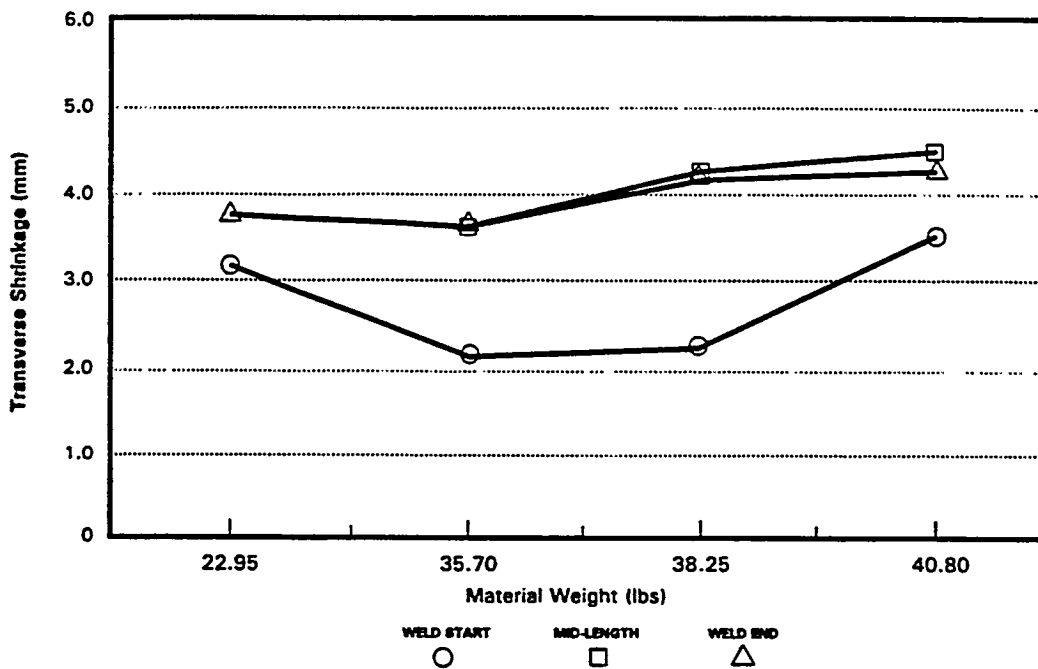
VERTICAL V-GROOVE ERECTION SHELL BUTTS



SHRINKAGE HISTOGRAM OF ERECTION JOINTS

Material Thickness - The mean transverse shrinkage by material thickness is illustrated in the graph. The transverse shrinkage increases slightly with increasing material thickness. The graph also shows the start location in each case has a lower amount of transverse shrinkage than the remainder of the weld joints. This fact can be controlled through restraint and welding sequence or compensated for in the erection procedure.

VERTICAL V-GROOVE ERECTION SHELL BUTTS



MEAN TRANSVERSE SHRINKAGE OF MATERIAL WEIGHT GROUPS

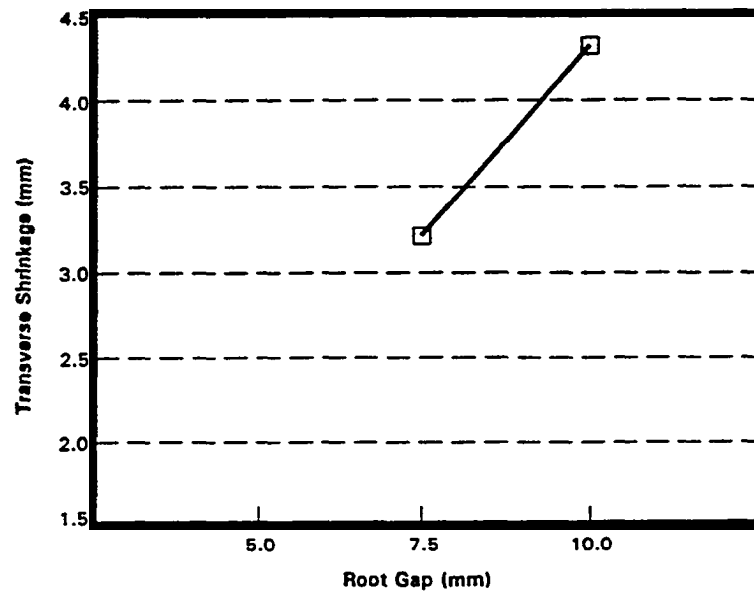
The mean shrinkage by joint location within this group is:

JOINT LOCATION	WELD START	MID-LENGTH	WELD END
MEAN SHRINKAGE	2.90	4.05	3.96

INDEPENDENT VARIABLES:

Joint Root Gap - Analysis of the mean shrinkage by joint gap illustrates a sharp increase in transverse shrinkage as the joint gap increases.

VERTICAL V-GROOVE ERECTION SHELL BUTTS



TRANSVERSE SHRINKAGE PER JOINT ROOT GAP

Joint Restraint Conditions - Typical restraint consisted of one sliptype stud fitting aid per three (3) feet.

Weld Heat Input - The welding heat input has not been considered as a variable in this analysis, because it was fairly consistent within the process studied. However, it is a key variable that must be included whenever there is a change in the welding process or the weld procedure.

Multiple Regression of Transverse Shrinkage:

Transverse shrinkage is regressed by each material weight group per joint location, and average joint root gap equal to 7.5 mm.

Shrinkage increases significantly at the mid-length and weld end locations. This condition can be controlled through outside restraint conditions and by modifying the welding sequence. This is often compensated during the erection process by the erection procedure.

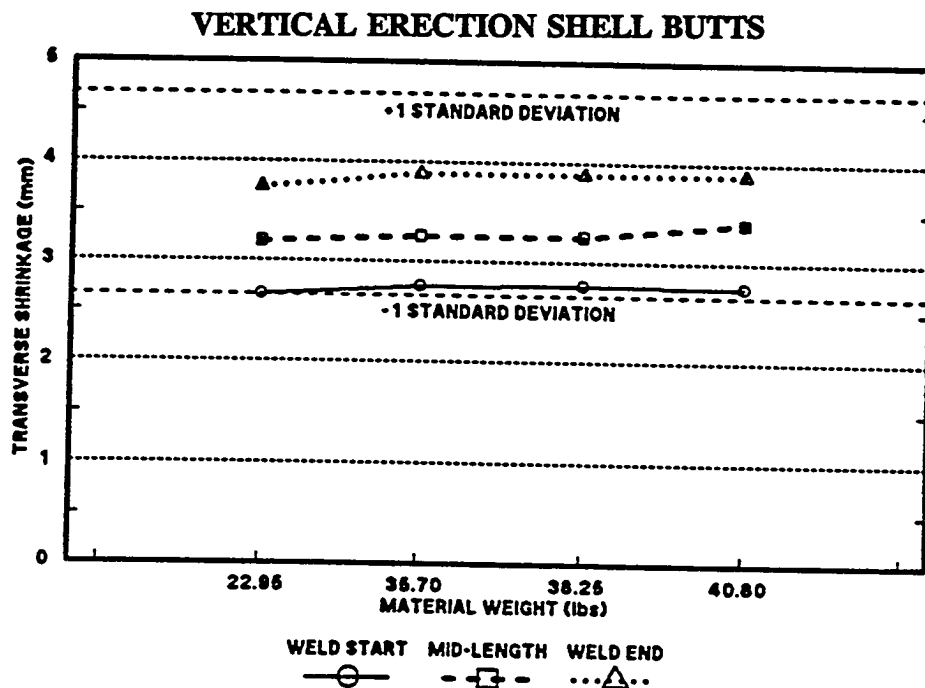
Predicted shrinkage is also regressed for 10.0 mm joint gaps less common in the shrinkage data set.

Regression Results:

• Constant	=	0.234290
• Standard Error of Y Estimate	=	0.668210
• R Squared	=	0.563958
• Number of Observations	=	23
• Degrees of Freedom	=	19

		<u>MATERIAL</u> <u>THICKNESS</u>	<u>JOINT GAP</u>	<u>JOINT</u> <u>LOCATION</u>
• X Coefficient	=	0.008912	0.544471	0.283962
• Standard Error of Coefficient	=	0.029260	0.170511	0.108043

Predicted Shrinkage:



PLOTTED REGRESSION OF PREDICTED SHRINKAGE

BLOCK SHELL BUTTS - PREDICTED SHRINKAGE
(ALL MEASUREMENTS IN MILLIMETERS)

MATERIAL WEIGHT, 22.95 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
7.5	2.6	3.2	3.7
10.0	3.4	3.9	4.4

MATERIAL WEIGHT, 35.70 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
7.5	2.8	3.3	3.9
10.0	3.5	4.0	4.6

MATERIAL WEIGHT, 38.25 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
7.5	2.8	3.3	3.9
10.0	3.5	4.0	4.6

MATERIAL WEIGHT, 40.80 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
7.5	2.8	3.4	3.9
10.0	3.5	4.1	4.6

VERTICAL ERECTION SHELL BUTT DATA SET

PRE-WELD JOINT GAP AND LOCATIONS OF SHRINKAGE

(ALL MEASUREMENTS IN MILLIMETERS)

BLOCK ID #	MATERIAL WT.(LBS)	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES)
A2-248	22.95	7.5	3.13	—	—	7.5	3.79	45,000 - 55,000
A2-223	28.05/38.25	7.5	2.76	7.5	4.16	10.00	4.82	
A2-249	28.05/35.70	10.0	2.62	10.0	4.25	10.00	4.52	
A2-277	28.05/35.70	7.5	1.89	7.5	3.24	7.5	3.62	
A2-278	28.05/35.70	7.5	1.83	7.5	3.45	7.5	2.98	
A2-224	28.05/38.25	7.5	1.88	—	—	7.5	3.36	
A2-141	40.80	7.5	3.13	7.5	4.17	—	—	
A2-142	40.80	5.0	3.18	—	—	10.0	4.22	
A2-189	30.60/40.80	10.0	4.11	10.0	4.78	—	—	
A2-155	45.90	7.5	4.25	12.5	4.24	10.0	5.00	
A2-156	45.90	7.5	3.57	—	4.08	—	3.37	

4.3.2 HORIZONTAL SHELL SEAMS

COMMON WELDING ATTRIBUTES

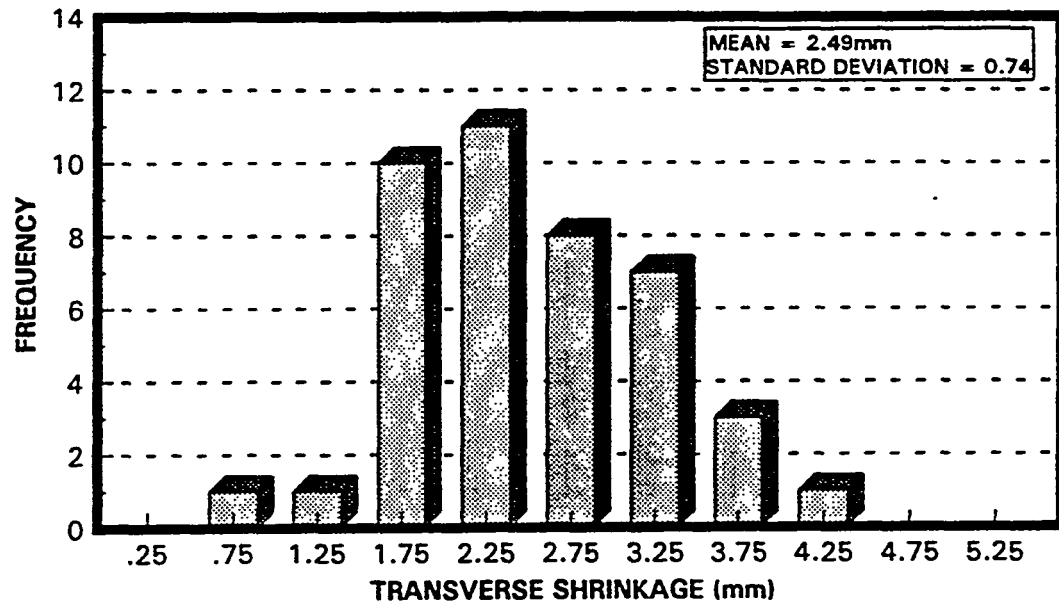
JOINT DESIGN	WELDING PROCESS	METHOD OF APPLICATION	JOINT POSITION
V-GROOVE (45° INCLUDED)	SMAW OR FCAW	MANUAL OR SEMI-AUT	HORIZONTAL

MATERIAL WEIGHT GROUPS (LBS)			
20.40	22.95	28.05	30.60

STANDARD WELDING PROCEDURE

Joint Design: Ref. Appendix Page 97 (see Joint Design B)
 Fitting Devices: Welded Strongbacks
 Design Joint Gap: 4.8mm

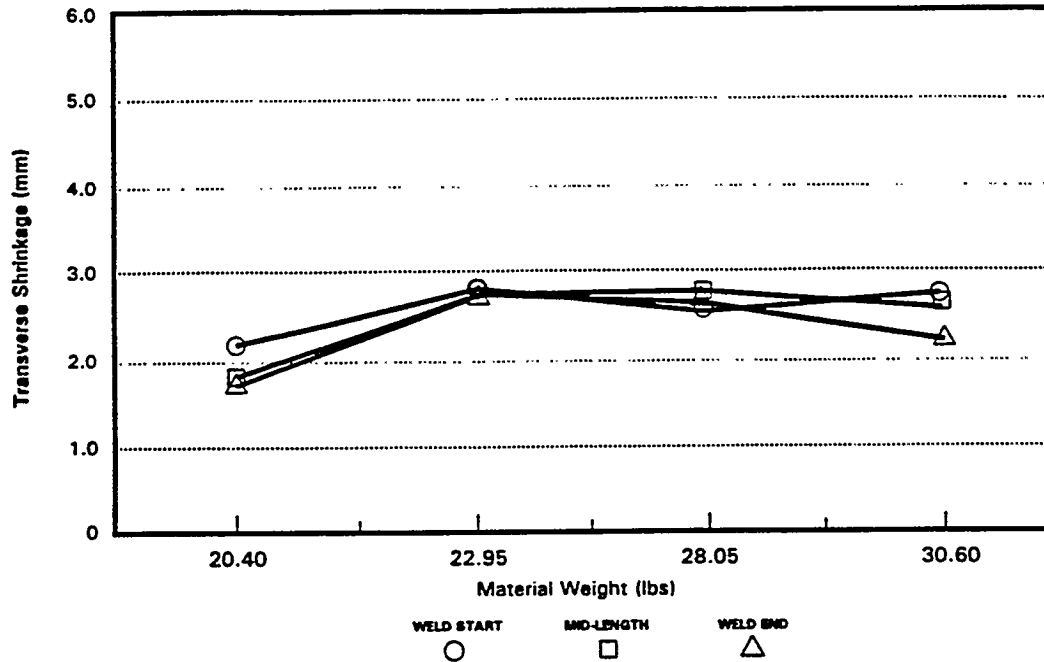
HORIZONTAL V-GROOVE ERECTION SHELL SEAMS



SHRINKAGE HISTOGRAM OF ERECTION JOINTS

Material Thickness - Transverse shrinkage increases slightly at material weights above 20.40 lbs. Within this data set the transverse shrinkage does not vary significantly along the joint location as with other joint positions.

HORIZONTAL V-GROOVE ERECTION SHELL SEAMS



MEAN TRANSVERSE SHRINKAGE BY MATERIAL WEIGHT GROUPS AND JOINT LOCATION

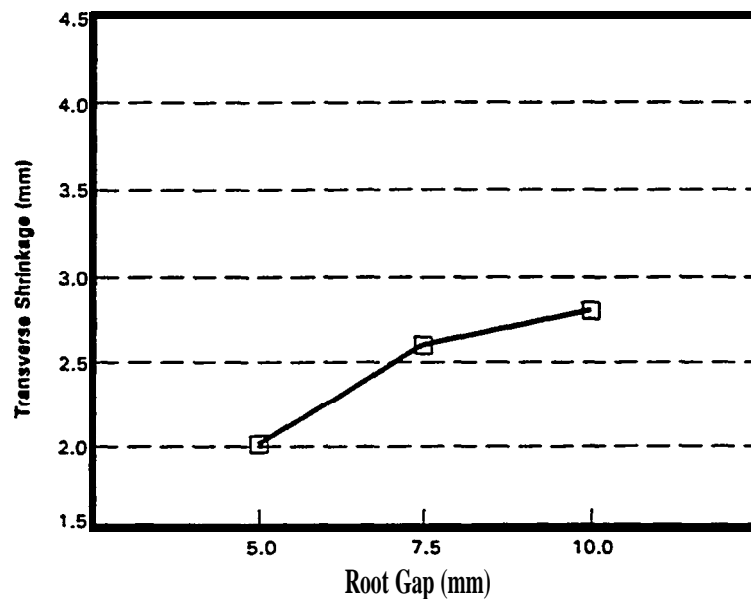
The mean shrinkage by joint location within this group is:

JOINT LOCATION	WELD START	MID-LENGTH	WELD END
MEAN SHRINKAGE	2.57	2.57	2.29

INDEPENDENT VARIABLES:

Joint Root Gap - Shell seam shrinkage increases steadily with the joint root gap. The joint gaps of 5.0mm to 10.0mm are a significant factor, causing almost 1mm of variance.

HORIZONTAL V-GROOVE ERECTION SHELL SEAMS



TRANSVERSE SHRINKAGE PER JOINT ROOT GAP

Joint Restraint Conditions - Localized joint restraining devices control transverse shrinkage and are consistent in their implementation with this joint position. The number of strongbacks was typically 20 per joint. This equated to one (1) welded strongback positioned 2' to 2 1/2' along each joint.

Weld Heat Input - The range of heat input is given in the shrinkage data set.

Multiple Regression of Transverse Shrinkage:

The independent variables included in the regression analysis are, material weight, joint location, and joint root gap. The calculated average root gap is equal to 7.5mm for 20.40 lb., 22.95 lb. and 30.60 lb. groups. The average joint gap of 28.05 lb material is 5.0mm. The predicted shrinkage reflects the reduced joint size as shrinkage takes a dip at the 28.05 lb. material weight.

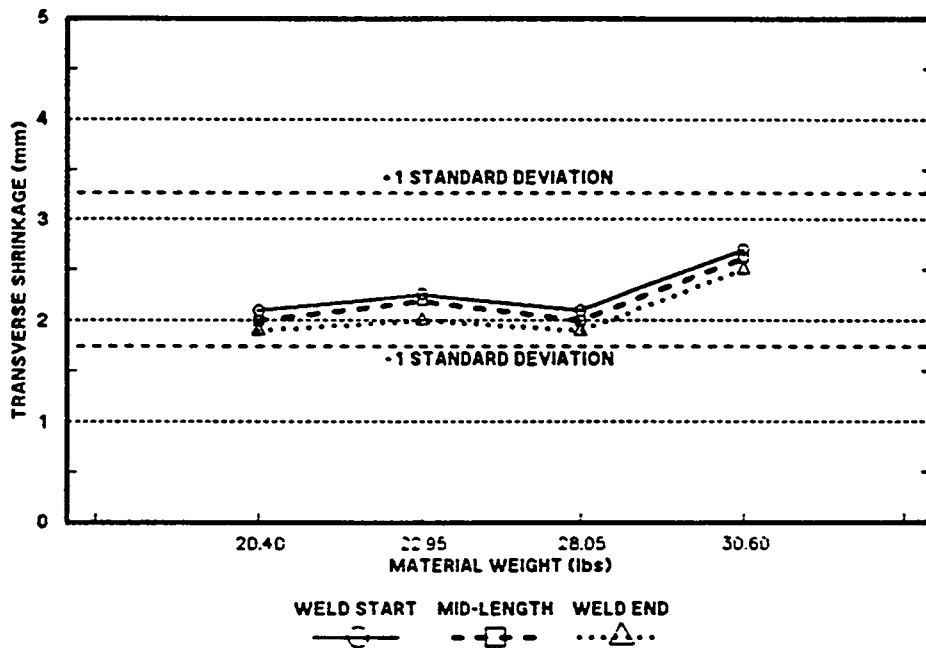
Regression results:

• Constant	=	0.830600
• Standard Error of Y Estimate	=	0.630195
• R Squared	=	0.262041
• Number of Observations	=	36
• Degrees of Freedom	=	32

		<u>MATERIAL</u> <u>THICKNESS</u>	<u>JOINT GAP</u>	<u>LOCATION</u>
• X Coefficient	=	0.853751	-0.113640	0.164583
• Standard Error of Coefficient	=	0.824628	0.132956	0.861342

Predicted Shrinkage:

HORIZONTAL ERECTION SHELL SEAMS



PLOTTED REGRESSION OF PREDICTED SHRINKAGE

**SHELL SEAMS - PREDICTED SHRINKAGE
(ALL MEASUREMENTS IN MILLIMETERS)**

MATERIAL WEIGHT, 20.40 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	1.7	1.6	1.5
7.5	2.1	2.0	1.9
10.0	2.6	2.4	2.3

MATERIAL WEIGHT, 22.95 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	1.9	1.8	1.6
7.5	2.3	2.2	2.0
10.0	2.7	2.6	2.5

MATERIAL WEIGHT, 28.05 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	2.1	2.0	1.9
7.5	2.6	2.4	2.3
10.0	3.0	2.8	2.7

MATERIAL WEIGHT, 40.80 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	2.3	2.2	2.0
7.5	2.7	2.6	2.5
10.0	3.1	3.0	2.9

HORIZONTAL ERECTION SHELL SEAM DATA SET

PRE-WELD JOINT GAP AND LOCATIONS OF SHRINKAGE

(ALL MEASUREMENTS IN MILLIMETERS)

BLOCK ID #	MATERIAL WT.(LBS)	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES)
A2-099	20.40	7.5	1.59	7.5	.71	7.5	1.12	45,000 - 55,000
A2-100	20.40	7.5	2.23	7.5	1.86	10.00	2.21	
A2-243	20.40	7.5	2.04	10.0	2.24	—	—	
A2-244	20.40	7.5	2.62	7.5	2.91	7.5	2.15	
A2-248	22.95	—	2.58	—	2.80	—	2.24	
A2-211	22.95	10.0	3.13	7.5	3.07	10.0	3.36	
A2-277	28.05	10.0	1.99	7.5	2.27	5.0	2.17	
A2-249	28.05	5.0	1.95	5.0	1.78	7.5	1.80	
A2-223	28.05	—	3.93	—	3.30	—	4.02	
A2-224	28.05	5.0	2.45	7.5	3.95	—	—	
A2-160	30.60	—	—	5.0	2.82	5.0	1.56	
A2-159	30.60	10.0	2.77	7.5	2.52	—	—	
A2-190	30.60	5.0	1.64	5.0	1.51	5.0	1.62	
A2-189	30.60	5.0	3.13	10.0	3.68	7.5	3.07	
A2-218	30.60	10.0	3.87	10.0	3.07	5.0	2.38	

4.3.3A FLAT DECK BUTTS: (LESS THAN OR EQUAL TO 20.4 LBS.)

COMMON WELDING ATTRIBUTES

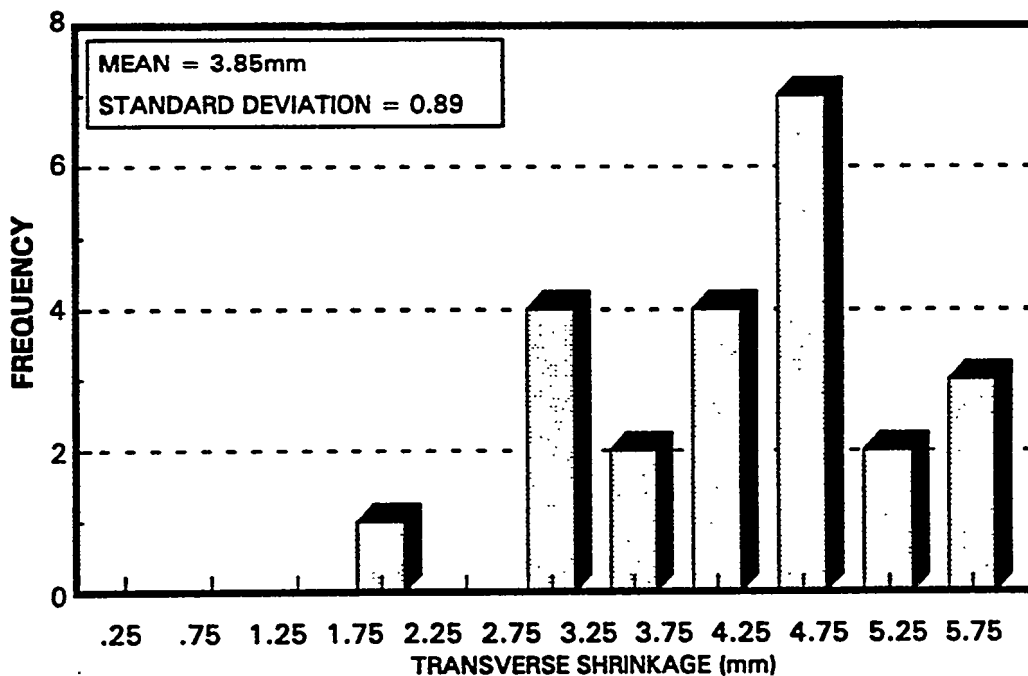
JOINT DESIGN	WELDING PROCESS	METHOD OF APPLICATION	JOINT POSITION
V-GROOVE (45° INCLUDED)	FCAW/SAW	SEMI-AUTOMATIC/ AUTOMATIC	FLAT

MATERIAL WEIGHT GROUPS (LBS)		
12.75	15.30	20.40

STANDARD WELDING PROCEDURE

Joint Design: Ref. Appendix Page 97 (see Joint Design B)
 Fitting Devices: Slip-Tight Stud Fitting Aids
 Design Joint Gap: 6.3mm

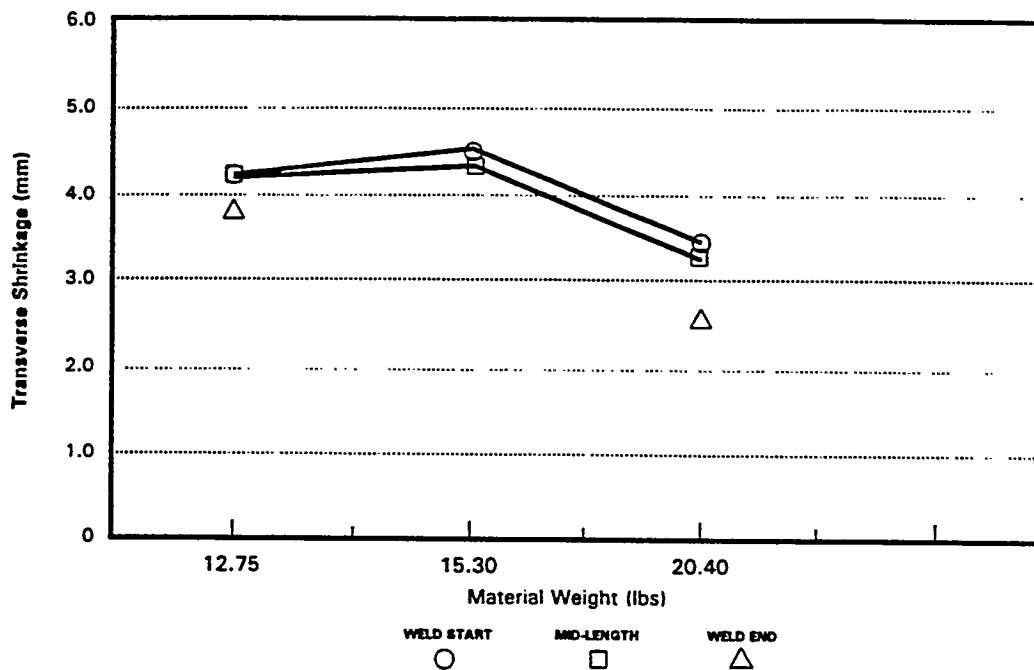
FLAT V-GROOVE ERECTION DECK BUTTS



SHRINKAGE HISTOGRAM OF ERECTION JOINTS

Material Thickness - This graph of mean shrinkage decreasing as the material weight groups increase illustrates an unusual shrinkage pattern. This condition is a result of the complex restraint variables surrounding the joints during the analysis, in addition, a combination of slip-type and welded strongbacks were used on various joints. Insight into the effect of this combination is explained through subsequent tests performed under laboratory condition provided in the following sections.

FLAT V-GROOVE ERECTION DECK BUTTS



MEAN TRANSVERSE SHRINKAGE BY MATERIAL WEIGHT GROUPS AND JOINT LOCATION

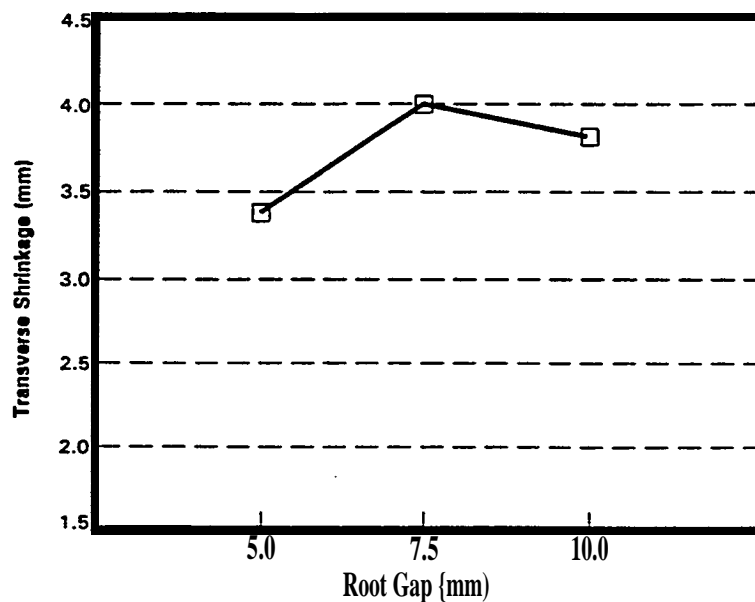
The mean shrinkage by joint location within this group is:

JOINT LOCATION	WELD START	MID-LENGTH	WELD END
MEAN SHRINKAGE	3.98	4.00	3.44

INDEPENDENT VARIABLES:

Joint Root Gap - This graph also illustrates an unusual decreasing shrinkage by joint root gap. Other variables during the welding process not defined attributed to this decline. As explained in the previous section the complex condition caused by various types of external restraint are attributed to this trend.

FLAT V-GROOVE ERECTION DECK BUTTS (12.75, 15.30 AND 20.40 LBS)



TRANSVERSE SHRINKAGE PER JOINT ROOT GAP

Joint Restraint Conditions - Typical restraint conditions consisted of a combination of stud-fitting aids and use of welded strongbacks, in high restraint areas.

Weld Heat Input - The range of heat input is given in the shrinkage data set.

Multiple Regression of Transverse Shrinkage:

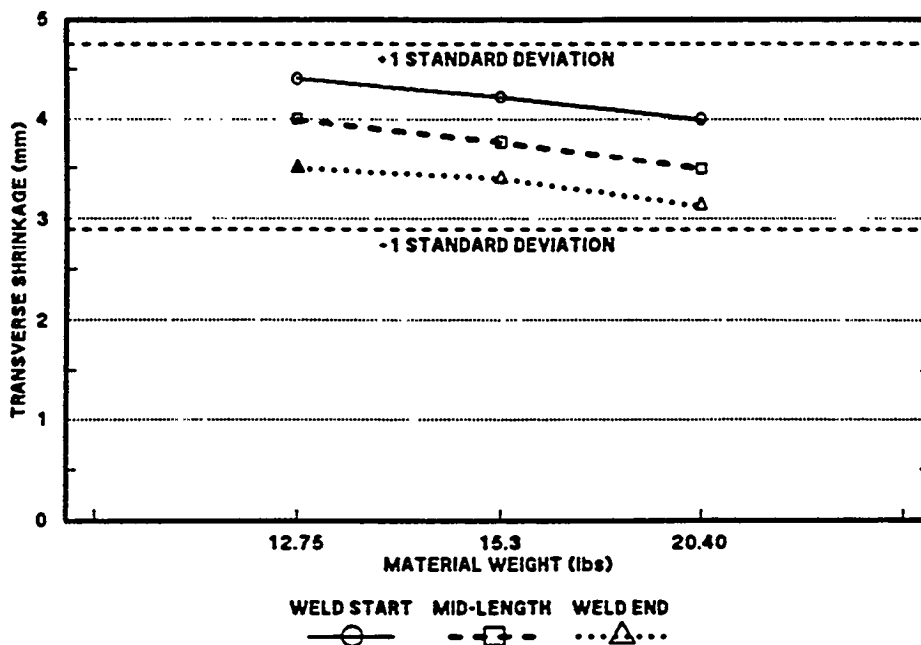
With the mean root gap of each material weight group equal to 7.5mm the results of the plotted regression illustrate this decrease in transverse shrinkage with increasing material weight. Conclusions based on results like this cannot be given without further analysis of the effect of the joint restraint condition.

Regression results:

• Constant	=	4.683240		
• Standard Error of Y Estimate	=	0.837684		
• R Squared	=	0.275753		
• Number of Observations	=	23		
• Degrees of Freedom	=	19		
		<u>MATERIAL</u>	<u>JOINT GAP</u>	<u>JOINT</u>
		<u>THICKNESS</u>		<u>LOCATION</u>
• X Coefficient	=	-0.05821	-0.44365	0.118619
• Standard Error of Coefficient	=	0.048356	0.238123	0.056932

Predicted Shrinkage:

FLAT ERECTION DECK BUTTS (12.75, 15.30 AND 20.40 LBS)



PLOTTED REGRESSION OF PREDICTED SHRINKAGE

**DECK BUTTS - PREDICTED SHRINKAGE
(ALL MEASUREMENTS IN MILLIMETERS)**

MATERIAL WEIGHT, 12.75 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	4.1	3.7	3.2
7.5	4.0	4.0	3.5
10.0	4.7	4.2	3.8

MATERIAL WEIGHT, 15.30 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	4.0	3.5	3.1
7.5	3.8	3.8	3.4
10.0	4.5	4.1	3.7

MATERIAL WEIGHT, 20.40 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	3.7	3.2	2.8
7.5	3.5	3.5	3.1
10.0	4.2	3.8	3.4

**FLAT ERECTION DECK BUTT DATA SET
PREWELD JOINT GAP AND LOCATIONS OF SHRINKAGE**

(ALL MEASUREMENT IN MILLIMETERS)

BLOCK ID#	MATERIAL WT.(LBS)	JOINT GAP	WELD START	JOINT GAP	MID LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES)
A2-170	12.75	7.5	4.49	7.5	5.26	10.0	4.09	55,000-65,000
A2-169	22.75	4.0		5.0	3.74	20.5	5.07	
A2-210	22.75	10.0	4.07	7.5	4.17	5.0	3.06	
A2-181	22.75	7.5	2.96	7.5	3.51	7.5	3.01	
A2-182	15.30	7.5	4.89	7.5	4.33	7.5	7.66	
A2-188	15.30	5.0	4.64	5.0	4.46	—	—	
A2-243	15.30	10.0	3.86	10.0	4.07	10.0		
A2-100	20.40	7.5	5.03	10.0	3.99	10.0	2.63	
A2-119	20.40	5.0	1.90	5.0	2.51	7.5	2.75	

4.3.3B FLAT DECK BUTTS: (GREATER THAN 20.4 LBS.)

COMMON WELDING ATTRIBUTES

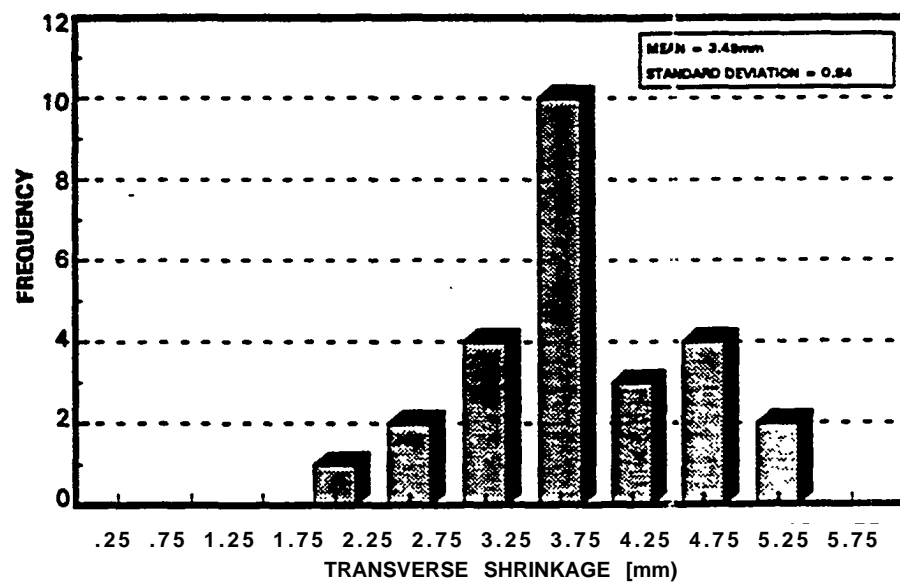
JOINT DESIGN	WELDING PROCESS	METHOD OF APPLICATION	JOINT POSITION
V-GROOVE (45° INCLUDED)	FCAW/SAW	SEMI-AUTOMATIC/ AUTOMATIC	FLAT

MATERIAL WEIGHT GROUPS (LBS)		
35.70	38.25	40.80

STANDARD WELDING PROCEDURE

Joint Design: Ref. Appendix Page 97 (see Joint Design B)
Fitting Devices: Slip-Type Stud Fitting Aids
Design Joint Gap: 6.3mm

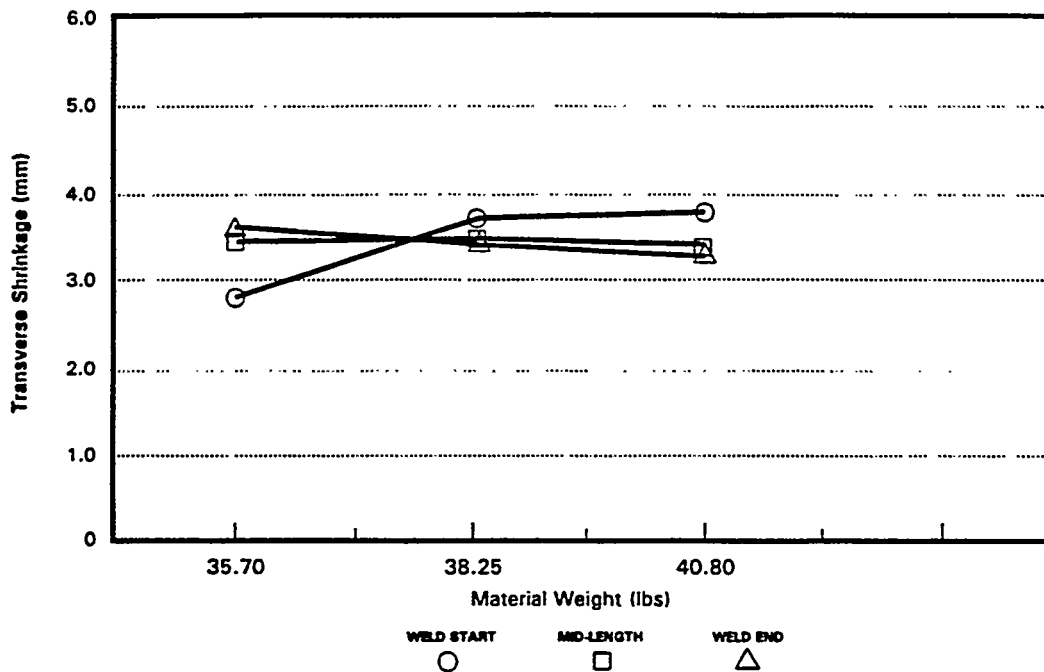
FLAT V-GROOVE ERECTION DECK BUTTS



SHRINKAGE HISTOGRAM OF ERECTION JOINTS

Material Thickness - In this range of material weights shrinkage remains stable. The major cause of variance at each of the joint locations will be determined.

FLAT V-GROOVE ERECTION DECK BUTTS



MEAN TRANSVERSE SHRINKAGE BY MATERIAL WEIGHT GROUPS AND JOINT LOCATION

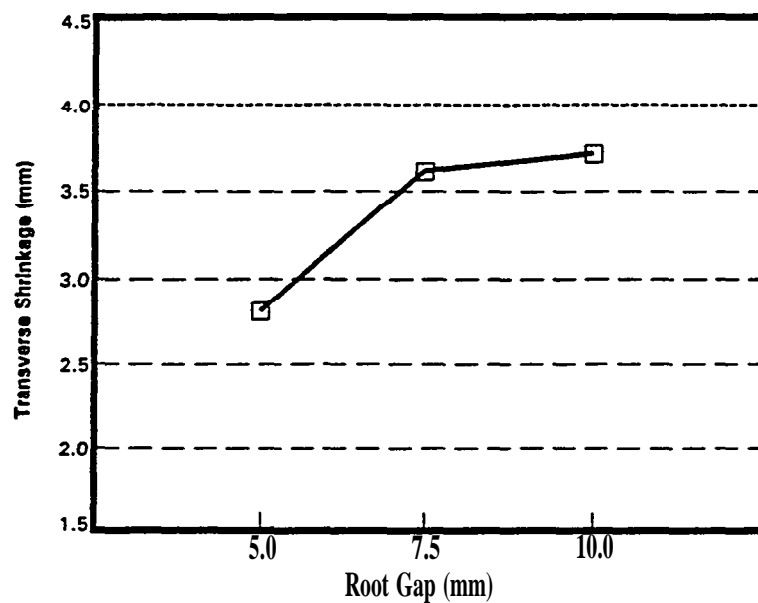
The mean shrinkage by joint location within this group is:

JOINT LOCATION	WELD START	MID-LENGTH	WELD END
MEAN SHRINKAGE	3.72	3.44	3.26

INDEPENDENT VARIABLES:

Joint Root Gap - The mean transverse shrinkage increases almost 1mm as the root gap increases from 5.0mm to 10.0mm.

FLAT V-GROOVE ERECTION DECK BUTTS



TRANSVERSE SHRINKAGE PER JOINT ROOT GAP

Joint Restraint Conditions - Typical restraint conditions consisted of a combination of welded strongbacks and slip-type stud fitting aids.

Weld Heat Input - The range of heat input is given in the shrinkage data set.

Multiple Regression of Transverse Shrinkage:

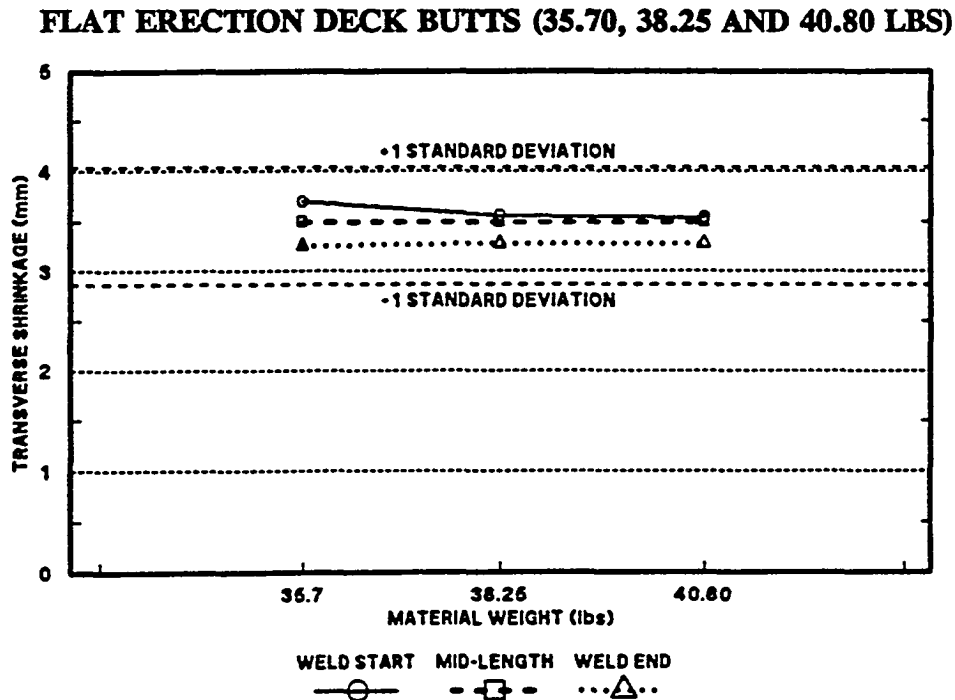
Regression results:

• Constant	=	2.327831
• Standard Error of Y Estimate	=	0.618909
• R Squared	=	0.206778
• Number of Observations	=	25
• Degrees of Freedom	=	21

		MATERIAL THICKNESS	JOINT GAP	JOINT LOCATION
• X Coefficient	=	-0.00217	-0.15770	0.140990
• Standard Error of Coefficient	=	0.062700	0.156833	0.069064

Predicted Shrinkage:

Predicted shrinkage for the three (3) common root gaps is given on the next page.



PLOTTED REGRESSION OF PREDICTED SHRINKAGE

DECK BUTTS - PREDICTED SHRINKAGE
(ALL MEASUREMENTS IN MILLIMETERS)

MATERIAL WEIGHT, 35.70 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	3.3	3.1	3.0
7.5	3.7	3.5	3.3
10.0	4.0	3.8	3.7

MATERIAL WEIGHT, 38.25 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	3.3	3.1	3.0
7.5	3.6	3.5	3.3
10.0	4.0	3.8	3.7

MATERIAL WEIGHT, 40.80 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	3.3	3.1	3.0
7.5	3.6	3.5	3.3
10.0	4.0	3.8	3.7

**FLAT ERECTION DECK BUTT DATA SET
PRE-WELD JOINT GAP AND LOCATIONS OF SHRINKAGE**

(ALL MEASUREMENTS IN MILLIMETERS)

BLOCK ID #	MATERIAL WT.(LBS)	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES)
A2-238	35.70	7.5	2.93	10.0	3.29	7.5	3.57	55,000 - 65,000
A2-278	35.70	—	—	7.5	3.49	5.0	3.62	
A2-223	38.25	5.0	3.03	10.0	3.41	10.0	3.62	
A2-224	38.25	7.5	4.32	7.5	3.14	10.0	3.29	
A2-272	38.25	7.5	4.16	7.5	3.87	—	—	
A2-160	40.80	—	—	10.0	3.13	7.5	2.76	
A2-184	40.80	7.5	3.42	7.5	3.17	5.0	2.25	
A2-218	40.80	10.0	4.75	—	—	10.0	4.48	
A2-189	40.80	—	—	7.5	4.65	7.5	4.09	
A2-217	40.80	7.5	3.42	5.0	2.84	5.0	2.44	

4.3.4A FLAT DECK SEAMS: (LESS THAN OR EQUAL TO 20.4 LBS.)

COMMON WELDING ATTRIBUTES

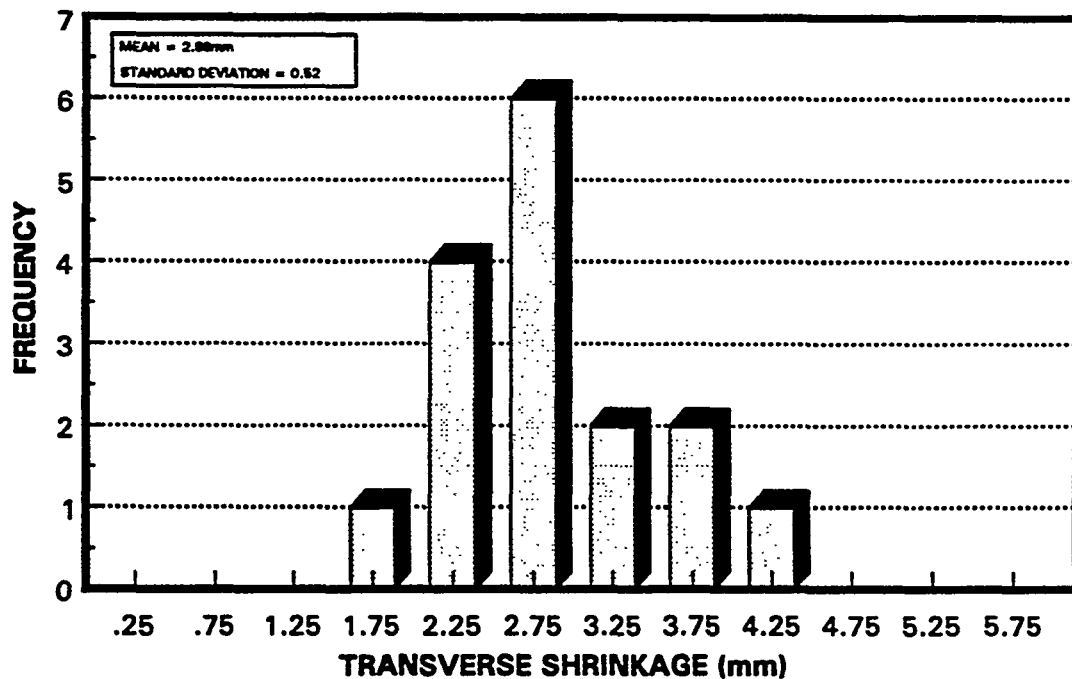
JOINT DESIGN	WELDING PROCESS	METHOD OF APPLICATION	JOINT POSITION
V-GROOVE (45° INCLUDED)	FCAW/SAW	SEMI-AUTOMATIC/ AUTOMATIC	FLAT

MATERIAL WEIGHT GROUPS (LBS)	
15.30	20.40

STANDARD WELDING PROCEDURE

Joint Design: Ref. Appendix Page 97 (see Joint Design B)
Fitting Devices: Slip-Tight Stud Fitting
Design Joint Gap: 6.3mm

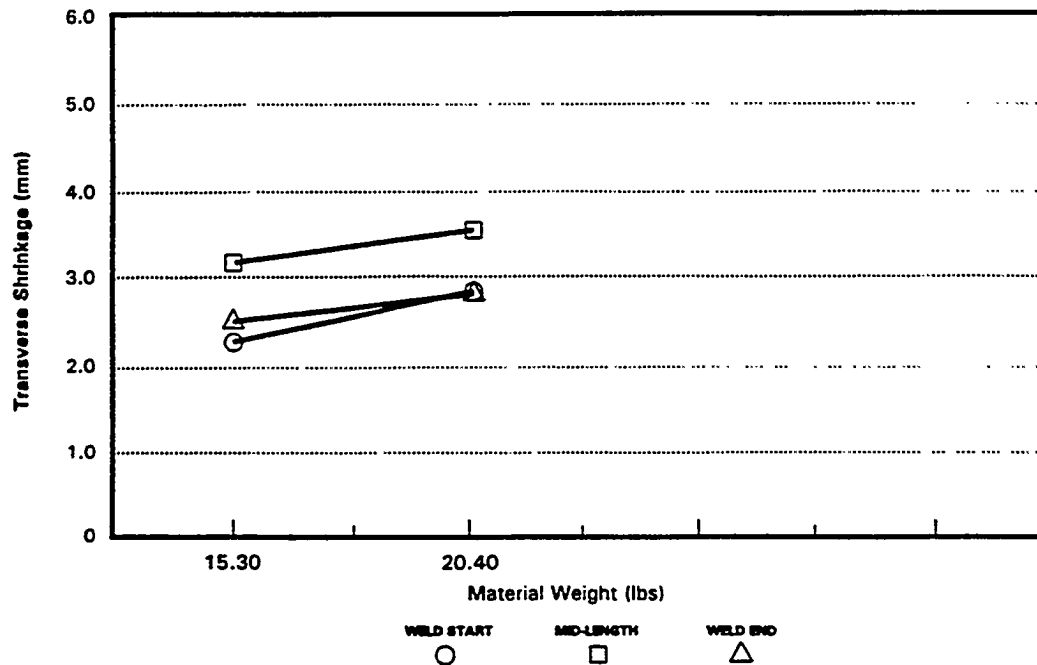
FLAT V-GROOVE ERECTION DECK SEAMS



SHRINKAGE HISTOGRAM OF ERECTION JOINTS

Material Thickness - Another unusual trend is sighted in the graph below with a greater mean shrinkage at the mid-length location.

FLAT V-GROOVE ERECTION DECK SEAMS



MEAN TRANSVERSE SHRINKAGE BY MATERIAL WEIGHT GROUPS AND JOINT LOCATION

The mean shrinkage by joint location within this group is:

JOINT LOCATION	WELD START	MID-LENGTH	WELD END
MEAN SHRINKAGE	2.61	3.32	2.61

INDEPENDENT VARIABLES:

Joint Root Gap - This data set had only three (3) recorded pre-weld joint gaps not equal to 7.5mm so shrinkage by this variable is not analyzed.

Joint Restraint Conditions - Typical restraint conditions consisted of 10 to 20 slip-tight stud fitting aids, positioned 2 1/2' to 3' apart.

Weld Heat Input - The range of heat input is given in the shrinkage data set.

Multiple Regression of Transverse Shrinkage:

One independent variable is not included unlike the other erection joint regressions, the joint root gap. The increase in shrinkage is a result of the increased 20.40 lb. material joint size.

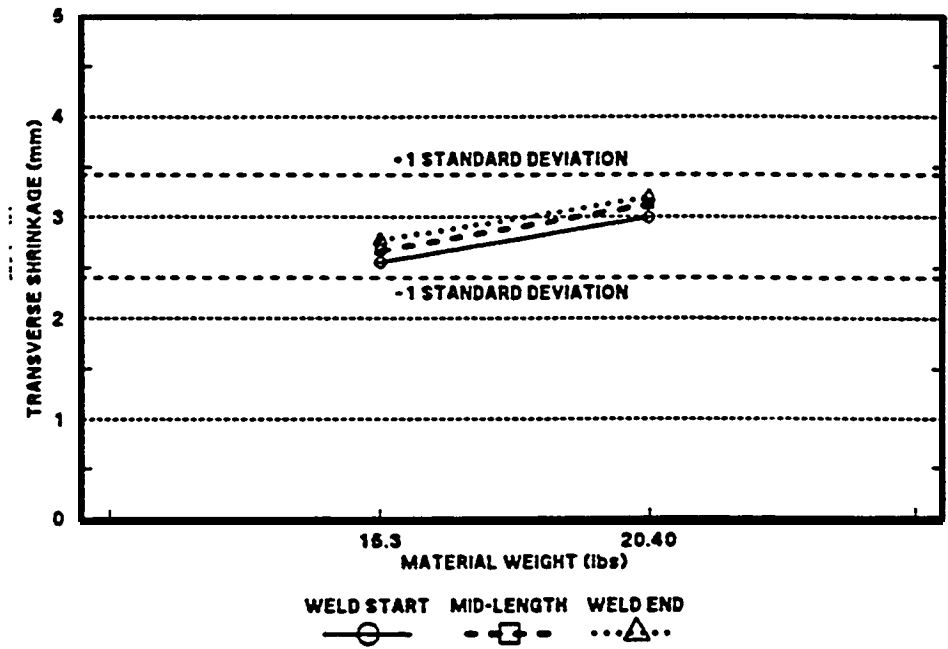
Regression results:

- Constant = 0.341618
- Standard Error of Y Estimate = 0.637246
- R Squared = 0.155801
- Number of Observations = 14
- Degrees of Freedom = 10

		MATERIAL THICKNESS	JOINT GAP	JOINT LOCATION
• X Coefficient	=	0.082247	0.081639	0.534859
• Standard Error of Coefficient	=	0.069471	0.241106	0.062958

Predicted Shrinkage:

FLAT ERECTION DECK SEAMS (15.30 and 20.40 LBS



PLOTTED REGRESSION OF PREDICTED SHRINKAGE

DECK SEAMS - PREDICTED SHRINKAGE
(ALL MEASUREMENTS IN MILLIMETERS)

MATERIAL WEIGHT, 15.30 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
7.5	2.6	2.7	2.8

MATERIAL WEIGHT, 20.40 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
7.5	3.0	3.1	3.2

**FLAT ERECTION DECK SEAM DATA SET
PRE-WELD JOINT GAP AND LOCATIONS OF SHRINKAGE**

(ALL MEASUREMENTS IN MILLIMETERS)

BLOCK ID #	MATERIAL WT.(LBS)	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES)
A2-235	15.30	7.5	2.29	7.5	3.37	7.5	2.75	55,000 - 65,000
A2-213	15.30	5.0	1.82	5.0	2.48	10.0	2.20	
A2-236	15.30	7.5	2.83	7.5	3.36	—	—	
A2-100	20.40	7.5	2.47	7.5	2.59	7.5	2.88	
A2-119	20.40	7.5	2.74	7.5	4.15	—	—	
A2-248	20.40	7.5	3.51	—	3.95	—	—	

4.3.4B FLAT DECK SEAMS

COMMON WELDING ATTRIBUTES

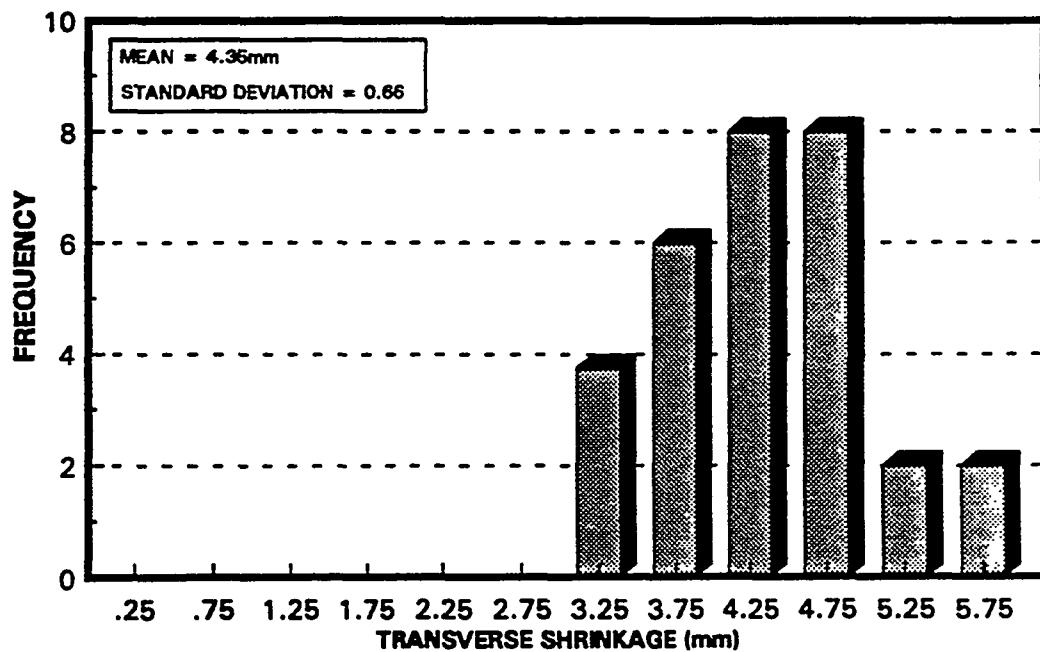
JOINT DESIGN	WELDING PROCESS	METHOD OF APPLICATION	JOINT POSITION
V-GROOVE (45° INCLUDED)	FCAW/SAW	SEMI-AUTOMATIC/ AUTOMATIC	FLAT

MATERIAL WEIGHT GROUPS (LBS)			
35.70	38.25	40.80	45.90

STANDARD WELDING PROCEDURE

Joint Design: Ref. Appendix Page 97 (see Joint Design B)
Fitting Devices: Slip-Tight Stud Fitting Aids
Design Joint Gap: 6.3mm

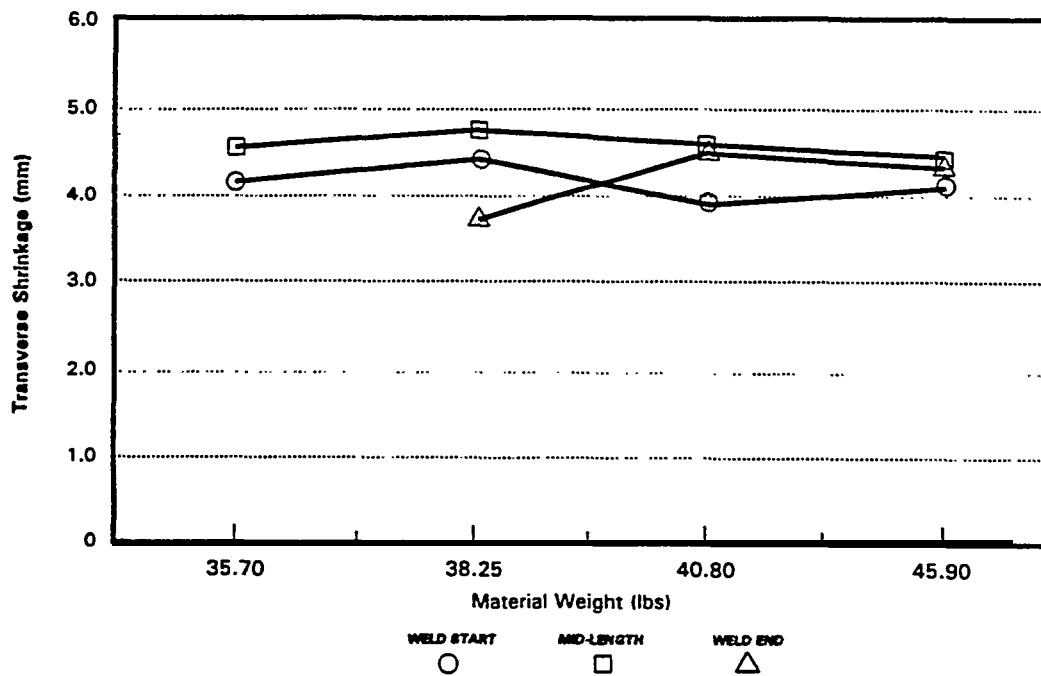
FLAT V-GROOVE ERECTION DECK SEAMS



SHRINKAGE HISTOGRAM OF ERECTION JOINTS

Material Thickness - Shrinkage levels are very close with respect to the material group range. The charts indicate mean shrinkage at each of the joint locations is not influenced significantly by the material weight, but is influenced by the joint gap variance as shown in the subsequent graphs.

FLAT V-GROOVE ERECTION DECK SEAMS



MEAN TRANSVERSE SHRINKAGE BY MATERIAL WEIGHT GROUPS AND JOINT LOCATION

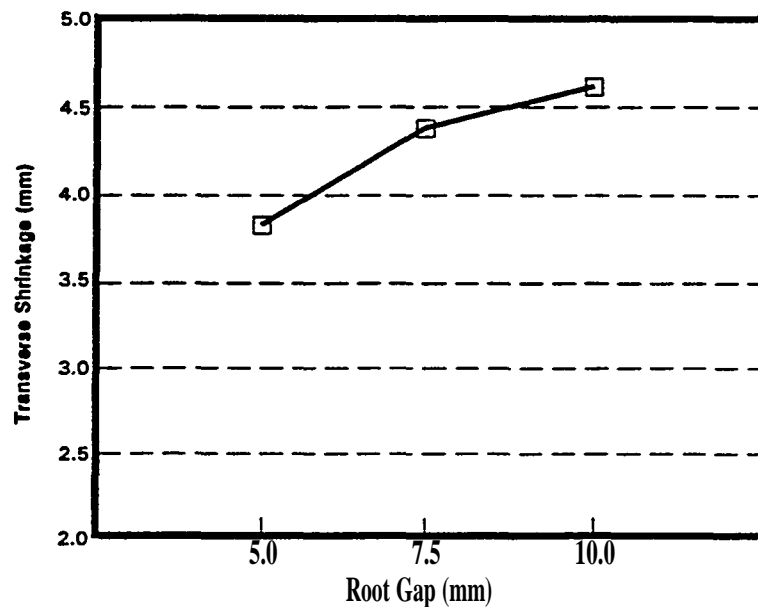
The mean shrinkage by joint location within this group is:

JOINT LOCATION	WELD START	MID-LENGTH	WELD END
MEAN SHRINKAGE	4.12	4.61	4.31

INDEPENDENT VARIABLES:

Joint Root Gap - The expected relationship is seen again with the root gap increase transverse shrinkage increases as well.

FLAT V-GROOVE ERECTION DECK SEAMS



TRANSVERSE SHRINKAGE PER JOINT ROOT GAP

Joint Restraint Condition - Typical restraint condition consisted of slip-type stud fitting aids, positioned 2 1/2' to 3' apart.

Weld Heat Input - The range of heat inputs is given in the shrinkage data set.

Multiple Regression of Transverse Shrinkage:

Shrinkage levels are very consistent when considering the 7.5mm mean joint gap. In the 38.25 lb material grouping transverse shrinkage increases as expected with the mean root gap of 100mm.

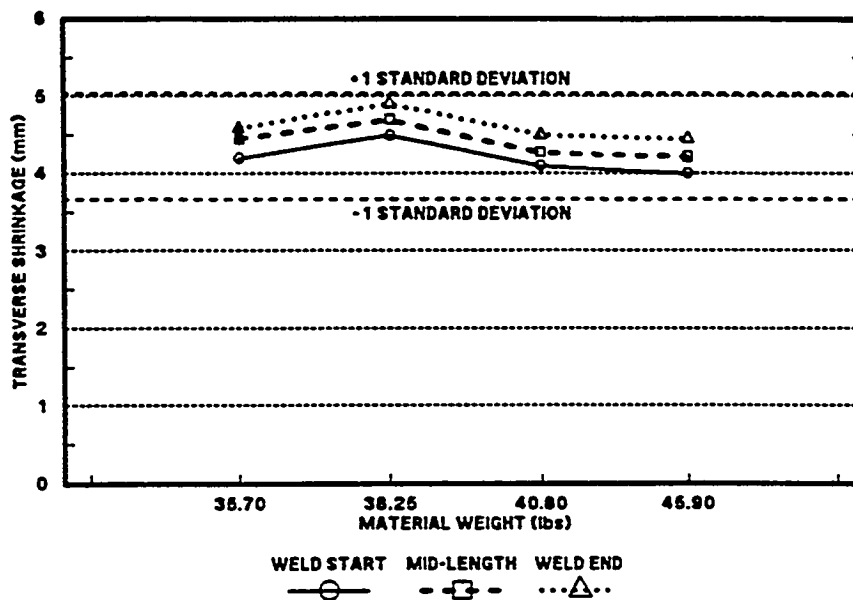
Regression results:

• Constant	=	3.69433
• Standard Error of Y Estimate	=	0.667433
• R Squared	=	0.194070
• Number of Observations	=	29
• Degrees of Freedom	=	25

		<u>MATERIAL</u> <u>THICKNESS</u>	<u>JOINT GAP</u>	<u>JOINT</u> <u>LOCATION</u>
• X Coefficient	=	0.022157	-0.002993	0.150640
• Standard Error of Coefficient	=	0.039266	0.166836	0.065908

Predicted Shrinkage:

FLAT ERECTION DECK SEAMS (35.70, 38.25, 40.80 AND 45.90 LBS)



PLOTTED REGRESSION OF PREDICTED SHRINKAGE

DECK SEAMS - PREDICTED SHRINKAGE
(ALL MEASUREMENTS IN MILLIMETERS)

MATERIAL WEIGHT, 35.70 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	3.8	4.0	4.2
7.5	4.2	4.5	4.6
10.0	4.6	4.8	5.0

MATERIAL WEIGHT, 38.25 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	3.8	4.0	4.2
7.5	4.2	4.3	4.5
10.0	4.5	4.7	4.9

MATERIAL WEIGHT, 40.80 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	3.7	3.9	4.1
7.5	4.1	4.3	4.5
10.0	4.5	4.7	4.9

MATERIAL WEIGHT, 45.90 LBS.

ROOT GAP	WELD START	MID-LENGTH	WELD END
5.0	3.6	3.8	4.0
7.5	4.0	4.2	4.4
10.0	4.4	4.6	4.7

FLAT ERECTION DECK SEAM DATA SET

PRE-WELD JOINT GAP AND LOCATIONS OF SHRINKAGE

(ALL MEASUREMENT IN MILLIMETERS)

BLOCK ID #	MATERIAL WT.(LBS)	JOINT GAP	WELD START	JOINT GAP	MID-LENGTH	JOINT GAP	WELD END	HEAT INPUT (JOULES)
A2-265	30.60/35.00	10.0	4.98	7.5	4.69	—	—	55,000-65,000
A2-250	35.70	5.0	3.28	5.0	4.53	—	—	
A2-224	38.25	12.5	5.15	7.5	4.61	10.0	3.28	
A2-223	38.25	10.0	3.78	7.5	4.90	—	4.15	
A2-160	40.80	7.5	4.19	7.5	4.41	10.0	5.26	
A2-159	40.80	—	—	7.5	4.15	7.5	3.14	
A2-1S9	40.80o	5.00	3.58	7.5	3.98	5.0o	4.13	
A2-218	40.80	10.0	3.83	10.0	5.87	7.5	5.89	
A2-217	40.80	10.0	4.29	7.5	4.86	7.5	4.15	
A2-141	45.90	—	—	7.5	3.92	—	—	
A2-155	45.90	5.0	3.54	7.5	4.00	7.5	4.33	
A2-156	45.90	10.0	4.64	10.0	4.75	—	—	

4.4 INDEPENDENT VARIABLES:

The welding heat input could be included in the analysis but because of the volume of data and the fixed ranges per data set, it was not included for the expediency of this study.

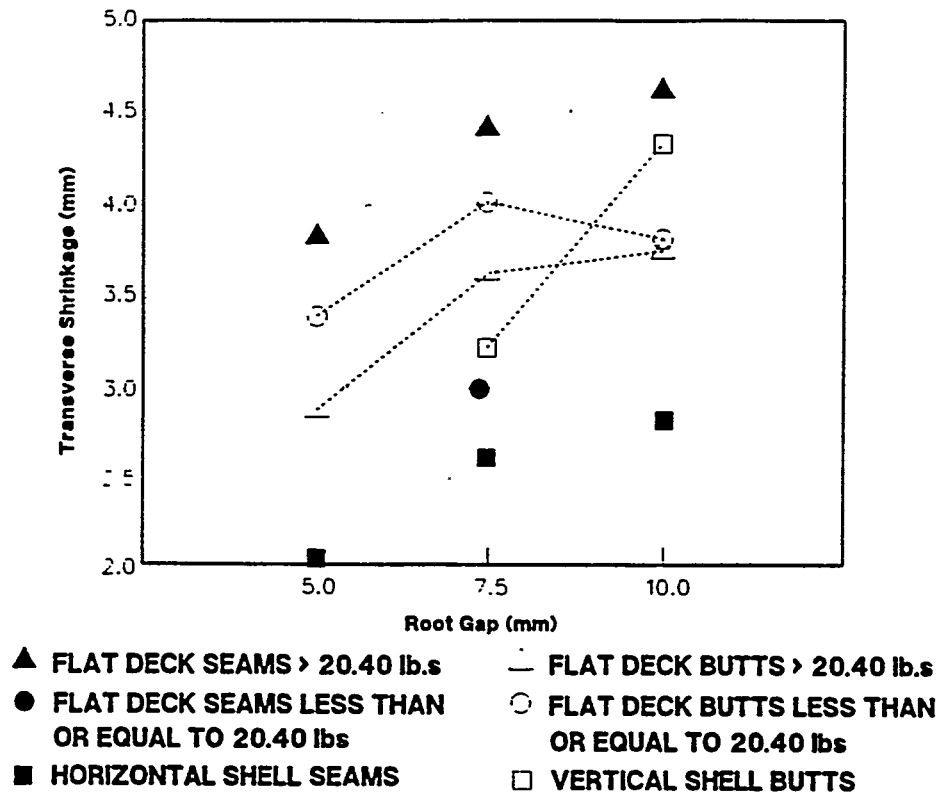
The next variable relates directly to the joint size. The pre-weld root gap fluctuates in the range of 5.0mm to 10.0mm significantly affecting the joint size. Four (4) of the data sets reveal the relationship expected with increasing joint root gap and the increase in transverse weld shrinkage (Figure 4-6).

Erection deck joints (butts and seams) are commonly fit with the slip-tight stud fitting aids where as horizontal shell seams are fit-up with welded strongbacks which produce greater levels of restraint. The lower shrinkage levels of shell seams are evident in the graph. Shrinkage variations of flat deck seam joints exist because of the combination of restraint types and inconsistency of application to suit erection requirements yet the mean shrinkage of deck butts at each joint gap size is less than 1mm despite the range of joint material weights.

The condition of joint restraint influence the degree of weld joint shrinkage in a number of ways. The size and weight of an erection block together with its positioning and surrounding environment produce varying levels of restraint that will influence the degree of weld shrinkage.

Localized restraint which is not applied consistently, that is the type and number of joint fitting aids, the number, size, and spacing of tack welds will influence shrinkage. These forms of joint restraint are localized will control shrinkage levels so that shrinkage factors can be established. In the experimental testing phase of this project the spread of shrinkage was analyzed with controlled restraint.

ALL ERECTION JOINTS



TRANSVERSE SHRINKAGE PER JOINT ROOT GAP

- FIGURE -4-6 -

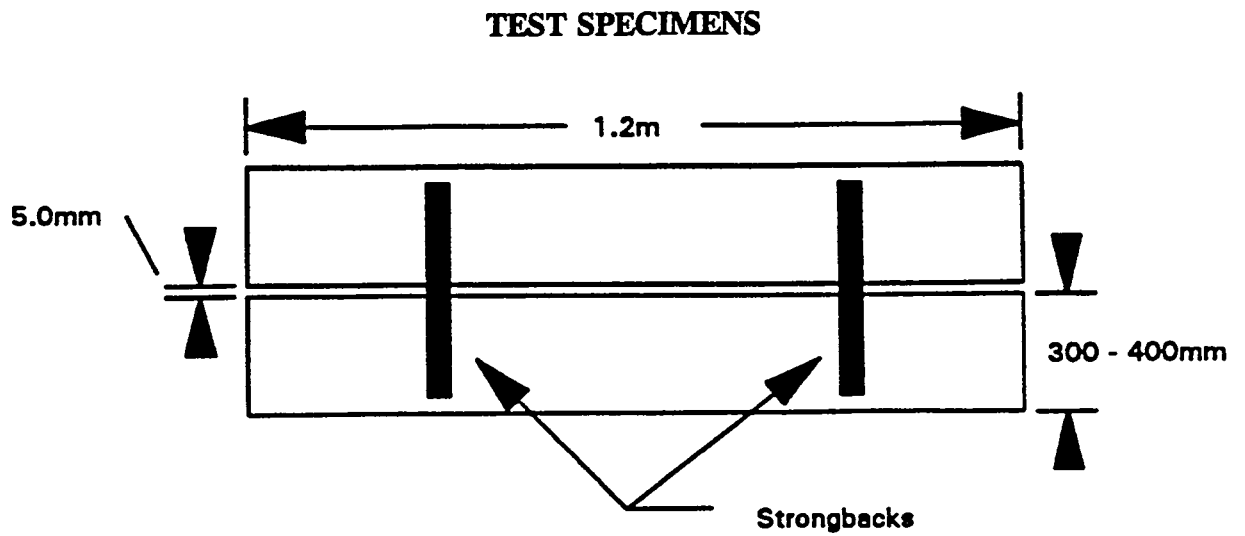
5.0 EXPERIMENTAL TESTING

The intent of this experimental testing was to gather shrinkage data taken from joints welded with two levels of heat input to illustrate the significance this independent variable can have on the spread of shrinkage with two levels of joint restraint applied. Erection joints have other forms of restraint more complex, created by outside conditions that cannot be altered. In these test conditions, restraint is controlled by a common tack size and two strongbacks. There is also a test joint welded at a high heat input with restraint controlled by a common tack size only.

Shrinkage results were obtained from test joints welded with the common attributes used for the erection deck joints. The joint design, the welding process, the method of welding application and the joint position are all common. This comparative analysis of shrinkage was evaluated for a range of common material weights.

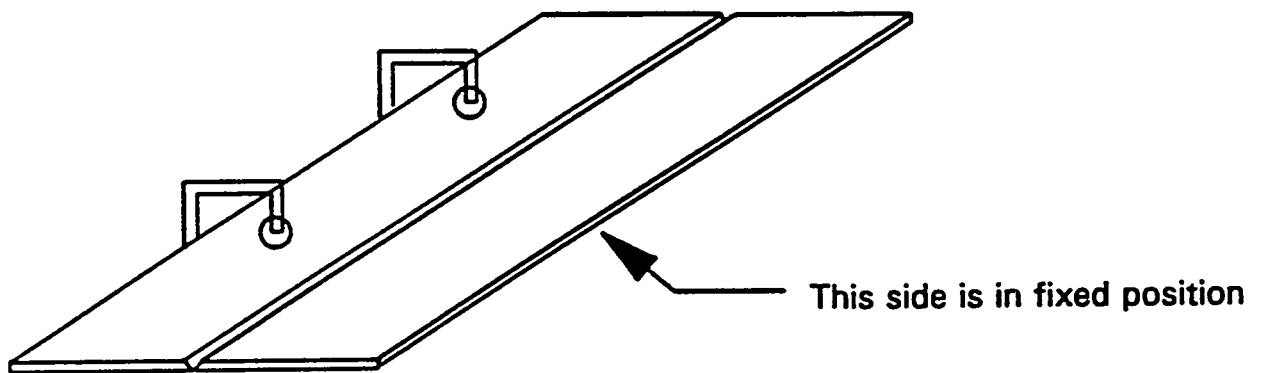
Test assemblies were welded under restraint conditions with two strong backs positioned 200mm from the joint ends. Test assemblies welded under no restraint conditions did not have strongbacks. Instead two rollers were positioned above one side of the test joint in the direction of transverse shrinkage (see Figure 5-2). Rotational distortion was controlled with two (2) freed wheels positioned on one side of the plate, however, transverse shrinkage for the most part was unaffected because the wheels moved freely in this direction.

Transverse shrinkage data is collected from three locations along each joint. Two positions, weld start and weld end measurements are in the same location as the strongbacks. The mid-length location is in the area of least restraint.



Test Assembly - With restraint conditions

-Figure 5-1 -



Test Assembly - No restraint conditions

- Figure 5-2 -

WELDING VARIABLES:

COMMON ATTRIBUTES:

Joint Design • 45° included V-Groove
Welding Process - SAW
Method of Application - One-sided welding on ceramic tile.
Welding Position - Flat
Material Weight - 20.40,30.60,40.80, and 51.00 lbs.

INDEPENDENT ATTRIBUTES:

Restraint Conditions - With or without strongbacks.
Heat Input -45,000 Joules and 60,000 Joules.

ADJUSTED VARIABLES

TEST ASSEMBLY ID GROUPS	RESTRAINT CONDITION	HEAT INPUT
A	RESTRAINT	LOW
B	RESTRAINT	HIGH
C	NONE	HIGH

TRANSVERSE SHRINKAGE

PLATE WEIGHT	• SHRINKAGE (mm) OF TEST ASSEMBLIES		
(LBS)	A	B	C
20.40	2.38	3.12	3.75
30.60	2.51	3.41	4.08
40.80	2.30	2.77	5.05
51.00	2.32	3.19	6.64

* Transverse shrinkage is the average of three (3) measurement locations, weld start, mid-length and weld end.

TEST RESULTS:

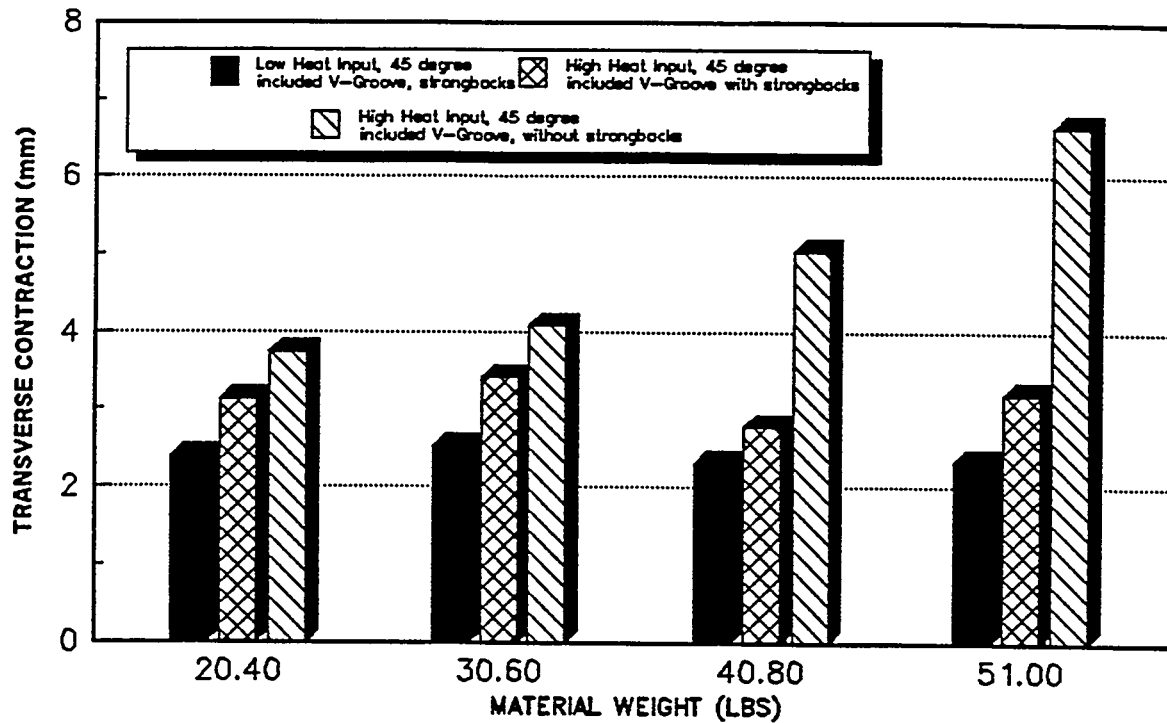
This data provides useful information on the range of shrinkage variance under fixed conditions (controlled variables). Transverse shrinkage results for each test are shown in Figure 5-3. With reduced weld heat-input, base metal dilution is lower. Although lower heat inputs will require a greater number of passes increasing the number of thermal cycles, greater shrinkage cannot be expected. Comparing joint group A and B which have the same joint design and are welded with the same deposition rates, greater shrinkage levels are resultant of higher heat input.

Comparison of transverse shrinkage between joints of the same design (45 degree included) produces a shrinkage spread over 3mm. The shrinkage spread between joints welded with strongbacks at low deposition and high deposition heat inputs is less than 1mm. When the joint has no restraint (no strongbacks) the shrinkage levels increase dramatically. Establishing reasonable factors for shrinkage with this variance is not possible.

Erection block joints having potentially higher levels of shrinkage can have shrinkage controlled (reduced) with proper fitting and welding techniques. By control of these unrestrained conditions, that is with proper fitting methods, overall joint shrinkage is reduced and shrinkage variance is controlled.

The usefulness of this data can only be used as pre-cursor to further testing. Knowing the shrinkage in a maximum restraint condition, developed from these tests and the shrinkage data collected for the third interim process, other fitting methods can be adapted.

**TRANSVERSE SHRINKAGE RANGE ILLUSTRATED
FOR
JOINTS WITH AND WITHOUT STRONGBACKS**



EXPERIMENTAL TEST

- Figure 5-3 -

6.0 CONCLUSION

If the welding attributes are not identical from shipyard to shipyard the weld shrinkage factors developed in one yard, cannot be implemented in another yard, without analysis. Although the welding application may be common other uncommon attributes may affect shrinkage levels.

1st INTERIM PROCESS:

The degree of variability within the process is very high with respect to the mean shrinkage, so shrinkage factors must be designed to account for this variability. Predicted shrinkage factors are provided for both the one-sided and two-sided applications. These factors are regressed from the design attributes. The mean and standard deviation are computed from the shrinkage data sets using the design attributes.

SHRINKAGE FACTORS - ONE-SIDED WELDING -

COMMON ATTRIBUTES:

Joint Design	Squared Butt
Welding process	SAW
Method of Application	One Sided Welding
Joint Position	Flat (no back gouging)

CHANGING ATTRIBUTES:

Material Thickness (lbs)	10.20, 15.30, 20.40
Welding Parameters	(Adjusted by Material Weight)
Joint Gap	0.0mm
Restraint Conditions	1/2" Tacks spaced every 2'

REGRESSION RESULTS

MATERIAL WEIGHT (LBS.)	10.20	15.30	20.40
SHRINKAGE FACTOR(mm)	0.9	1.0	1.2

CALCULATED

MEAN(x)	STANDARD DEVIATION
0.97	0.25

SHRINKAGE FACTORS - TWO-SIDED WELDING

COMMON ATTRIBUTES:

Joint Design	Square Butt
welding Process	SAW
Method of Application	Two sided welding
Joint Position	Flat (no back gouging)

CHANGING ATTRIBUTES:

Material Thickness (lbs)	12.75, 15.30, 20.40, 25.5
welding Parameters	(Adjusted by Material Weight)
Joint Gap	0.0mm
Restraint Condition	1/2" Tacks spaced every 2'

REGRESSION RESULTS

MATERIAL WEIGHT (LBS.)	12.75	15.30	20.40	25.50
PREDICTED SHRINKAGE (mm)	0.9	0.9	0.7	0.6

CALCULATED

MEAN (X)	STANDARD DEVIATION
0.71	0.40

2ND INTERIM PROCESS:

Transverse panel shrinkage in the second interim process lies within a range of 1.25 mm is difficult to predict. The histograms of shrinkage data is an illustration of the lack of symmetry within this process. (Page 35)

Remembering that loss in design dimension from distortion is not accounted for. The Second Interim Process here, has the highest degree of variability. Variability is even higher when considering plate distortion another factor in overall loss of plate length. With continuous high deposition welding processes distortion can be reduced but plate shrinkage will always be part of the process.

3RD INTERIM PROCESS:

Predicted shrinkage factors for this specified joint design are provided for erection joints. The shrinkage factor for each welding application must be considered together with the standard deviation for that process. If the deviation is too large the shrinkage factor is useless.

Independent variables in the regression analysis are the material thickness and joint gap, for the weld start, mid-length, and weld end locations. The shrinkage factors are given for each erection block joint position by the material thickness.

SHRINKAGE FACTORS

- DECK JOINTS -

COMMON ATTRIBUTES:

Joint Design	Single V-Groove (45°included)
Welding Process	SAW
Method of Application	one sided welding, Ceramic Tile
Joint Position	Flat

CHANGING ATTRIBUTES:

Material Thickness	Listed below
Welding Parameters	Heat Input (55,000-65,000Jti)
Joint Gap	7.5mm
Restraint Condition	(Fitting & ds a ad EXter=d~)

ERECTION DECK BUTTS

REGRESSION RESULTS

MATERIAL WEIGHT (LBS)	12.75	15.30	20.40
SHRINKAGE FACTOR (mm)	4.4	4.1	3.5

CALCULATED

MEAN (x)	STANDARD DEVIATION
4.04	0.88

SHRINKAGE FACTORS

ERECTION DECK BUTTS

REGRESSION RESULTS

MATERIAL WEIGHT (LBS.)	35.70	38.25	40.80
SHRINKAGE FACTOR (mm)	3.4	3.7	4.1

CALCULATED

MEAN (X)	STANDARD DEVIATION
3.48	0.72

-ERECTION DECK SEAMS -

REGRESSION RESULTS

MATERIAL WEIGHT (LBS.)	15.30	20.40
SHRINKAGE FACTOR (mm)	3.1	3.2

CALCULATED

MEAN (X)	STANDARD DEVIATION
3.00	0.52

- DECK SEAMS -

REGRESSION RESULTS

MATERIAL WEIGHT (LBS.)	35.70	38.25	40.80	45.90
SHRINKAGE FACTOR (mm)	4.9	4.7	4.5	4.1

CALCULATED

MEAN (X)	STANDARD DEVIATION
4.37	0.61

SHRINKAGE FACTORS

- SHELL BUTTS -

COMMON ATTRIBUTES:

Joint Design	Single V-Groove (45° included)
Welding Process	SMAW, FCAW
Method of Application	One Sided Manual and Semi-Automatic, Ceramic Tile
Joint Position	Vertical

CHANGING ATTRIBUTES:

Material Thickness (lbs)	22.95, 35.70, 38.25, 40.80
Welding Parameters	Heat Input (40,000-50,000 Joules)
Joint Gap	7.5mm
Restraint Conditions	(Fitting Aids and External Restraint)

- SHELL BUTTS -

REGRESSION RESULTS

MATERIAL WEIGHT (LBS.)	22.95	35.70	38.25	40.80
SHRINKAGE FACTOR (mm)	3.4	3.7	3.7	3.8

CALCULATED

MEAN (X)	STANDARD DEVIATION
3.59	0.76

SHRINKAGE FACTORS

-SHELL SEAMS -

COMMON ATTRIBUTES:

Joint Design	Single V-Groove (45°included)
welding Process	SMAW, FCAW
Method of Application	one sided manual Semi- Automatic,Ceramic Tile
Joint Position	Horizontal

CHANGING ATTRIBUTES:

Material Thickness (lbs)	20.40,22.95, 28.05, 30.60
welding Parameters	Heat Input (30,000-40,000 Joules)
Joint Gap	7.5mm
Restraint Conditions	(Fittigs Aids and External Restraint)

-SHELL SEAMS -

REGRESSION RESULTS

MATERIAL WEIGHT (LBS)	20.40	22.95	28.05	30.60
SHRINKAGE FACTOR (mm)	2.1	2.3	2.6	2.8

CALCULATED

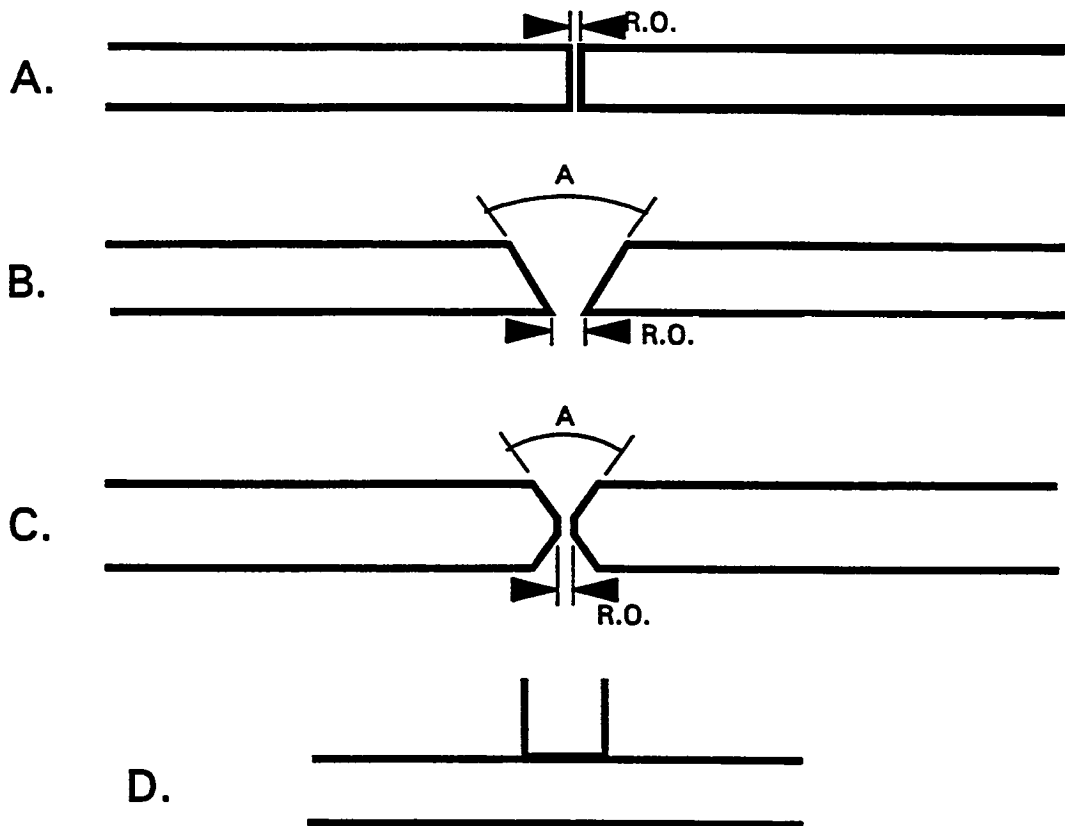
MEAN (X)	STANDARD DEVIATION
2.29	0.67

This study was conducted to provide a "how to" approach for the establishment of weld shrinkage factors. It is readily apparent that the relationship of the three independent variables on shrinkage can be analyzed much more thoroughly with a larger database and more included variables. R^2 is a measure of the percent variation the dependent variable has with the independent variables. This value is considered low in each data set analyzed. A better understanding of the percent variation would be approached by including more independent variables that might be attributable to weld shrinkage in the regression analysis.

Other variables that could be included under a more extensive analysis include: The weld heat-input, the deposition rate, and number of tacks and strongbacks along each joint. Although it is true more variables included in the regression analysis could increase the predictability of weld shrinkage, this may not be the case when considering the outside restraint conditions that cannot be controlled.

APPENDIX

WELD JOINT DESIGNS



- A. DOUBLE-SQUARE-GROOVE WELD
- B. SINGLE-V-GROOVE WELD
- C. DOUBLE-V-GROOVE WELD
- D. FILLET WELD

A = GROOVE ANGLE
R.O. = ROOT OPENING